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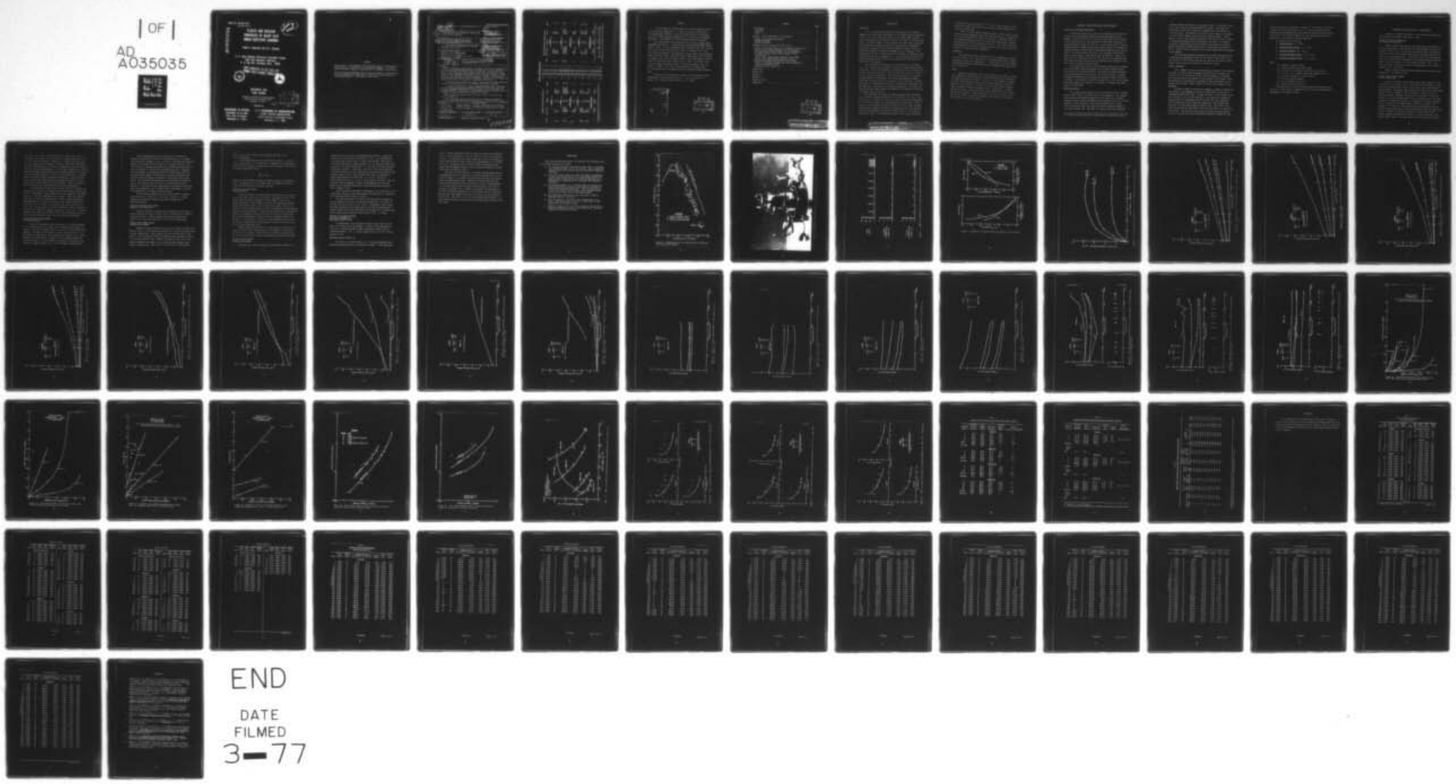

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PLASTIC AND RESILIENT PROPERTIES OF HEAVY CLAY UNDER REPETITIVE LOADINGS

Frank C. Townsend and Ed E. Chisolm

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Soils and Pavements Laboratory
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16. Abstract

This investigation was conducted to determine the effect of specimen stiffness on the relationship between elastic and plastic strain, rutting potential, and resilient modulus and Poisson's ratio of heavy clay. Specimens were compacted to various California Bearing Ratio (CBR) values and subjected to either 1,000 or 50,000 repetitive stress applications in a triaxial compression chamber. The plastic and recoverable strains were monitored from which the rutting potential and resilient modulus could be determined. CBR and unconfined compression strength (UCS) tests were conducted for supplemental information.

The plastic axial strains were found to increase with number and magnitude of axial stress repetitions and to be dependent upon specimen stiffness.

The resilient modulus was found to decrease initially with stress repetitions, followed in some cases by a gradual increase with additional repetitions. It was also dependent upon specimen stiffness, deviator stress magnitude, and confining pressure. The magnitude of conditioning stress up to 70 percent of the static UCS was found to have little effect on M_r values.

The relationship between elastic and plastic strain is dependent upon specimen stiffness.

Poisson's ratio was found to be insensitive to number and magnitude of repetitive stress applications, confining pressure, and specimen stiffness.

17. Key Words
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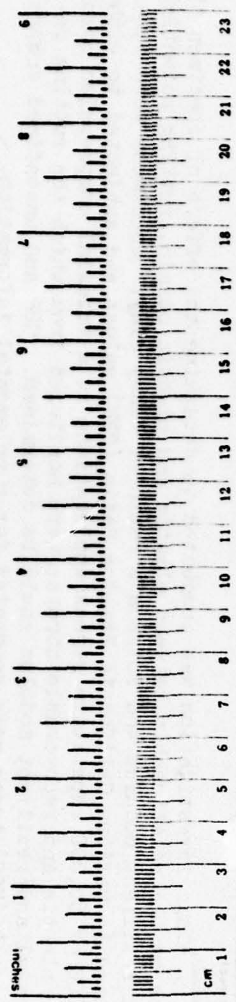
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

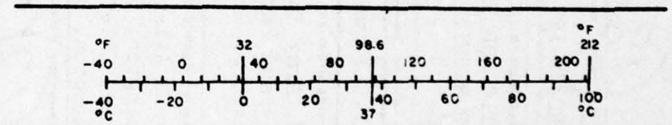
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The investigation reported herein was jointly sponsored by the Office, Chief of Engineers, U. S. Army, as a part of RDT&E Project No. 4A762719AT40, "Mobility, Soils, and Weapons Effects Technology," and by the Federal Aviation Administration as a part of Inter-Agency Agreement No. DOT FA73WAI-377, "New Pavement Design Methodology."

The investigation was conducted during the period August 1974-September 1975 by the U. S. Army Engineer Waterways Experiment Station (WES). Phase I of the investigation was conducted by Mr. Ed E. Chisolm, while Phase II was conducted by Dr. Frank C. Townsend, both of the Soils Research Facility, Soil Mechanics Division (SMD), Soils and Pavements Laboratory (S&PL), under the general supervision of Mr. Clifford L. McAnear, Chief, SMD, and Messrs. James P. Sale and Richard G. Ahlvin, Chief and Assistant Chief, respectively, of S&PL. Assisting in the testing program were Messrs. Robert D. Barnette, Henry B. Dent, and Willie J. Hughes. This report was prepared by Dr. Townsend and Mr. Chisolm for and in cooperation with the Pavement Design Division, S&PL.

Directors of WES during the conduct of the investigation and preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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INTRODUCTION

BACKGROUND

The U. S. Army Engineer Waterways Experiment Station (WES) is engaged in research under sponsorship of the Federal Aviation Administration and the Office, Chief of Engineers, U. S. Army (OCE), directed toward development of an improved procedure for design of flexible pavements. The first products of this research have been design procedures for all-bituminous concrete roads[1] and flexible airport pavements.[2] Both design procedures utilize limiting resilient strain criteria for limiting the amount of permanent deformation in the subgrade. This approach implies that a relationship exists between the permanent strain and resilient strain of subgrade soils. In both design procedures, the limiting subgrade strain criteria are presented as a function of the stiffness of the material.

The relationships between strain criteria and soil stiffness (i.e., the validity of the subgrade criteria) were questioned by other researchers. Since the dependency of subgrade criteria on stiffness had not been previously reported, it was felt that the validity of such a concept should be established. The procedure chosen was to establish through laboratory testing that the relationship between permanent strain and resilient strain is a function of soil stiffness. So that the report on the design procedure for flexible airport pavements could be completed, a first phase of testing was conducted. The results of these tests were used by Barker and Brabston[2] to establish the validity of subgrade strain criteria.

The procedure for design of airport pavements[2] was considered only an initial procedure which would be modified as the state of the art advances. Priority has since been placed on developing methodology for prediction of actual rut depths which will develop under traffic. Using the limited data available from Phase I of this study and other published data, Barker[3] developed a procedure with which the relationship between permanent strain and resilient strain could be used to predict rut depth. A more extensive analysis of rut depth prediction

procedures was conducted by Chou.[4] In both of these studies, predictions of rut depth were made for test sections having subgrades consisting of heavy clay.

Phase I of the study was conducted only to verify that the relationship between permanent strain and resilient strain is a function of soil stiffness measured in terms of a CBR value. Additional data on the deformation characteristics of heavy clay, particularly at higher repetitions levels, were collected in Phase II. The results from the investigation will be used to advance the state of the art in the prediction of rutting in airport pavements.

OBJECTIVE

The objective of this investigation was to determine the effect of soil stiffness (i.e., CBR value) on the relationship between elastic and plastic strain of a subgrade soil. Concurrently, resilient modulus and resilient Poisson's ratio values would be examined for effects due to soil stiffness.

SCOPE

Repeated load triaxial tests were conducted on specimens of heavy clay compacted at various moisture contents and densities to determine the elastic and plastic strains. In Phase I of the program, a maximum of 1,000 load repetitions under the unconfined compression mode were applied to each specimen. In Phase II, triaxial tests were conducted using a maximum of 50,000 load repetitions. Subsequently, the same specimens in Phase II were subjected to additional triaxial tests under various stress states. Elastic and plastic strains, resilient moduli, and Poisson's ratio values were determined and related to the various test parameters and soil properties.

MATERIAL, TESTING EQUIPMENT, AND PROCEDURES

MATERIAL AND SPECIMEN PREPARATION

The material tested was a heavy clay classified as CH under the Unified Soil Classification System and having Atterberg Limits as follows: liquid limit (LL) of 73, plastic limit (PL) of 25, and plasticity index (PI) of 48. This material has been used extensively as subgrade material in WES test sections. Since the objective of the investigation was to compare elastic and plastic strains of specimens of varying stiffness, the moisture content-density conditions were varied. Table 1 lists the molding conditions of the specimens tested during Phase I, while Table 2 lists similar data for Phase II. Figure 1 presents the CE 12 compaction curve for this soil and the conditions for the various batches and shows that all specimens were compacted on the "wet" side of optimum moisture content.

To determine the moisture content-density conditions for preparing 2.8-in.-diam* triaxial specimens, CBR specimens compacted under CE 12 effort were molded and tested. Based upon this CBR information, sufficient material to mold at least four 2.8-in.-diam by 6-in.-high specimens was prepared at the appropriate moisture content, sealed in a container, and allowed to cure for at least 24 hr. The test specimens were then compacted, as needed, in six layers to a density that would yield the desired CBR.

TESTING EQUIPMENT

The repeated load triaxial tests were conducted using a standard triaxial cell capable of testing 2.8-in.-diam specimens. The repeated axial stresses were applied pneumatically with WES cyclic triaxial equipment using a nearly rectangular stress-time wave form for a 0.2-sec duration at 3-sec intervals. The load was monitored by a 500-lb-capacity miniature load cell mounted inside the confining chamber on top of the specimen cap. The axial and radial strains were measured

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* A table for converting units of measurement is presented on page 4.

by matched LVDT's calibrated to the nearest 0.0001 in. and held in position on the specimen by spring-loaded LVDT clamps. The clamps were positioned so that axial strains were measured over the central 4 in. of the specimen. The geometry of the LVDT holding clamps is such that the radial LVDT's measure twice the actual diameter change. A small amount of Devcon 5-min epoxy was applied at the contact points to assist in preventing slippage between the membrane and clamp. Frictionless end plates incorporating polished stainless steel surfaces, silicone grease, and Teflon inserts were utilized to minimize end restraint effects. Figure 2 shows a specimen with the LVDT clamps ready for testing in the chamber.

The load and deformation response was recorded electronically on a light beam oscillograph recorder for the Phase I tests, while a hot-wire stylus HP 7700 8-channel recorder was used for the Phase II tests. Figure 3 shows typical recordings for the Phase II tests.

TESTING PROCEDURE

After compaction, each of the specimens was placed on the triaxial cell base; a 0.012-in.-thick membrane was placed on the specimen and sealed to the cap and base by O-rings; and the chamber was assembled. No confining pressure was applied to the specimens during Phase I tests. The specimens were subjected to a maximum of 1000 load repetitions at various stress levels. Table 1 shows the stress levels applied to the specimens.

Testing in Phase II consisted of applying a maximum of 50,000 load repetitions to the specimens at specified axial stress levels and a confining pressure of 2.0 psi. As shown in Table 2, these stress levels were usually 15, 35, 55, and 70 percent of the unconfined compressive strength (UCS), as determined from UCS tests on duplicate specimens. After application of the 50,000 load repetitions, each specimen was subjected to a multistage resilient modulus test. Each stage of the resilient modulus test consisted of 100 load repetitions of a specified stress state. The various stress states involved confining pressures of 2.0, 4.0, and 6.0 psi and five different deviator stresses for each

confining pressure (see Appendix A, Table A2). The plastic and elastic strains and resilient Poisson's ratio ν_r were calculated from the permanent and recoverable axial and radial deformations measured by the LVDT clamps. The resilient modulus M_r was calculated from the repetitive load and resilient axial deformations.

Calculations are as follows:

a. Plastic strain: $\varepsilon_p = \Delta H/H_o$

b. Resilient axial strain: $\varepsilon_{r1} = H_r/H_i$

c. Resilient modulus: $M_r = \sigma_{dc}/\varepsilon_{r1}$

d. Resilient lateral strain: $\varepsilon_{r3} = D_r/D_i$

e. Resilient Poisson's ratio: $\nu_r = \varepsilon_{r3}/\varepsilon_{r1}$

where

ΔH = permanent change in height

H_o = initial height between LVDT clamps

H_r = resilient or recoverable height for a given cycle

$H_i = H_o - \Delta H$, i.e., height between LVDT clamps for cycle n

D_r = resilient diameter for a given cycle

D_o = initial specimen diameter

$D_i = D_o + \Delta D$ diameter for cycle n

σ_{dc} = repetitive deviator stress

A seating stress of 0.6 psi was maintained on the specimen for the Phase I tests, while a seating stress of 2.0 psi was maintained on specimens for the Phase II tests.

PRESENTATION AND DISCUSSION OF TEST RESULTS

Appendix A together with Tables 1 and 2 shows the tabulated engineering data from Phase I and Phase II tests.

EFFECT OF MOISTURE CONTENT AND DRY DENSITY ON CBR AND UCS

Figure 4 presents the CBR and UCS relationship with moisture content and dry density. These results show that specimen stiffness, expressed as CBR or UCS, is a function of moisture content and density, with greater CBR and UCS values obtained with decreasing moisture contents and increasing densities. Also shown is the fact that specimen conditions between Phase I and Phase II tests were consistent with CBR values, with the exception of the specimens with CBR = 7.15. For these specimens, the moisture content was compatible, but the density appeared to be 1.4 pcf high.

Figure 5 presents the unconfined compression stress-strain relationships for the Phase II tests.

PLASTIC STRAIN VERSUS NUMBER OF LOAD REPETITIONS

Figures 6-9 present plastic axial strain versus number of load repetitions for the Phase I tests (1,000 repetitions maximum), and Figures 10-12 present similar data for the Phase II tests (50,000 repetitions maximum). In general, these figures show that plastic axial strain increases with the number of load repetitions. However, in two instances, as shown in Figures 10a and 10b for the Phase II tests, the smaller cyclic load produced greater plastic strains, which is contrary to general observations and logic. In explanation of these discrepancies, a comparison can be made between Specimen 8 of Phase I and Specimen 11 of Phase II. These specimens had approximately the same moisture content and density and were subjected to about the same cyclic stress. Specimen 11, Phase II, exhibited a plastic axial strain 10 times greater than Specimen 8, Phase I, on the first cycle. The plastic axial strain on the first cycle is critical since this strain

determines the position of the plastic axial strain versus number of load repetitions curve. In this context, the plastic axial strain for the first cycle of Specimen 11, Phase II, is judged to have been excessive, possibly due to seating or shifting of the LVDT clamp under the first load repetition. The data for Specimen 9, Phase II, are considered to be more representative. In the case of Specimen 10, Phase II, exhibiting greater plastic axial strain although subjected to a lesser cyclic stress than Specimen 12, Phase II (see Figure 10b), an examination of the data in Table 2 reveals that Specimen 12 was denser and had a lower moisture content than the averages for Batch VII; hence, lower plastic axial strain could be anticipated. The data for Specimen 10, Phase II, are therefore considered more representative.

An examination of these figures reveals that in no case was the repeated load sufficient to produce failure (with failure defined when the rate of permanent strain increased with each additional load repetition; i.e., the curve approached the vertical). Larew and Leonards[5] found that the ratio of repeated stress level to static compressive strength required to cause failure was greater than 88 percent for a micaceous silt, 85 percent for a residual clay, and 65 percent for a sandy clay. Brown, LaShine, and Hyde[6] found that a ratio in excess of 90 percent was required to produce failure for a silty clay. Since the maximum ratio tested for the Phase II tests was 70 percent, these results are consistent with those from the previous investigation.

RESILIENT MODULUS VERSUS NUMBER OF LOAD REPETITIONS

Figures 13-16 present resilient modulus M_r versus log number of load repetitions for the Phase I tests (1,000 cycles maximum), and Figures 17-19 present similar data for the Phase II tests (50,000 cycles maximum). The Phase I tests showed a slight initial decrease in M_r with number of repetitions, with practically no increase in M_r after obtaining a constant value. The Phase II tests likewise showed an initial decrease in M_r with number of repetitions, followed in some cases by a gradual increase in M_r after reaching a minimum value.

Early investigations at the University of California at Berkeley[7] concerning the effect of load repetitions on M_r showed that typically a decrease in M_r occurred to a minimum value somewhere between 1 and 10,000 cycles followed by an increase, which in some cases reached a limiting value after about 50,000 repetitions, but in others continued to increase after 250,000 repetitions. Specimens with high degrees of saturation subjected to high stress levels required a greater number of repetitions to achieve the minimum than specimens with low degrees of saturation tested under lower stress levels. The observed stiffening effect was attributed to densification of the specimen under the repetitive loads and thixotropy. However, for the tests of this investigation, the greatest stiffening effect was observed for the 3.7-CBR material (high degree of saturation) subjected to the higher repetitive loads.

Tests by Brown, LaShine, and Hyde did not exhibit a stiffening effect for M_r values of a silty clay. Rather, M_r values initially decreased and remained essentially constant up to 100,000 repetitions.

RESILIENT POISSON'S RATIO VERSUS NUMBER OF LOAD REPETITIONS

The data presented in Figures 17-19 reveal that unlike the resilient modulus, resilient Poisson's ratio is insensitive to number of stress repetitions. Similar observations have been reported by Dehlen[8] for a silty clay subjected to 25,000 stress repetitions.

PLASTIC AXIAL STRAIN VERSUS REPEATED AXIAL STRESS

Figures 20 and 21 present the plastic axial strain for Phase I and Phase II tests at 1,000 repetitions and Phase II tests after 50,000 repetitions, respectively. These results show that for both Phase I and Phase II tests the plastic strain was dependent upon specimen stiffness for a given repetitive load. However, the Phase II tests do not completely complement the Phase I tests concerning CBR; instead, three distinct groups occur: CBR = 2.4 to 3.7 (w = 30.5 to 33.1 percent),

CBR = 5.4 to 7.5 (w = 26.8 to 28.7 percent), and CBR = 13.8 (w = 24.1 percent).

The nonlinear shape of the repeated axial stress σ_d versus plastic axial strain ε_p relationship is suggestive of a hyperbola, as also observed by Ogawa.[9] He showed that the relationship could be expressed in hyperbolic form as

$$\frac{\varepsilon_p}{\sigma_d} = a + b\varepsilon_p$$

Figures 22 and 23 present the data of Figures 20 and 21 in hyperbolic form. Although the fit is less than ideal, the figures show that a hyperbola could be used to represent the data.

PLASTIC AXIAL STRAIN VERSUS RESILIENT STRAIN

Figure 24 presents the relationship between plastic and elastic strain for 1,000 repetitions in the Phase I and Phase II tests. Figure 25 presents similar information for the Phase II tests after 50,000 repetitions. These results show that the relationship between elastic and plastic strain is not constant for a given soil but is a function of soil strength, which, in turn, is dependent upon the molding moisture content and density. Hence, any design procedure predicated on limiting the permanent strain by limiting the resilient strain would have to vary the allowable resilient strain in accordance with soil strength. In other words, to obtain the same permanent strain for two CBR values of the same soil, the allowable resilient strain would have to be less for the weaker soil.[3]

Ogawa[9] found a similar effect of soil strength (or moisture content) on plastic versus elastic strain relationships for silty clay compacted wet of optimum. Brown, LaShine, and Hyde[6] also showed that the plastic versus elastic strain relationship was dependent upon CBR.

RESILIENT MODULUS VERSUS REPEATED AXIAL STRESS

Typically, for cohesive materials, the resilient modulus is

characterized as a function of repeated deviator stress. Figure 26 presents this relationship for the Phase I tests. Also presented are resilient modulus values equal to 1,560 times the CBR. Each point in this figure represents a single specimen with the resilient modulus calculated for the 1,000th repetition; i.e., the end of the WES procedure conditioning sequence. Conversely, the Phase II tests were subjected to 50,000 repetitions prior to imposing the various stress states of the resilient modulus tests. These 50,000 repetitions are analogous to 50,000 conditioning repetitions with $\sigma_3 = 2.0$ psi instead of 1,000 repetitions with $\sigma_3 = 0$ psi, as was used in the Phase I and conventional testing programs. Figures 27-29 summarize the resilient modulus versus repeated axial stress at various confining pressures for the Phase II tests.

These results for the Phase I and Phase II tests show that M_r is a function of deviator stress and specimen stiffness and to a lesser extent confining pressure (Phase II tests).

The results presented in Figures 27-29 show that the magnitude of the repeated axial stress during conditioning, up to 70 percent of the UCS, had little effect on M_r values. Furthermore, these results show that unloading from a higher axial stress during conditioning to a lower stress for resilient testing and returning to the original axial stress during conditioning has little effect on the M_r values.

EFFECTS OF SPECIMEN STIFFNESS AND APPLIED STRESSES ON RESILIENT POISSON'S RATIO

An examination of the resilient Poisson's ratio values for the Phase II test data listed in Appendix A reveals no distinguishing effects due to specimen stiffness (CBR), magnitude of axial load, or confining pressure. The ν_r values ranged from 0.23 to 0.47, with an average of 0.35.

RESILIENT MODULUS VERSUS UCS

The ratio of resilient modulus M_r to the static modulus from unconfined compression tests is presented in Table 3. Some inaccuracy

exists in these comparisons since the repetitive tests were conducted under a confining pressure of 2.0 psi, while the static tests were unconfined. Nevertheless, the results show that the resilient modulus is always greater than the static modulus by approximately 5 to 12 times. This is not surprising since the static modulus incorporates both plastic and recoverable strains, while the resilient modulus is based solely upon recoverable strains.

The ratio of static modulus to a modulus incorporating both the recoverable and plastic strains for the first load repetition is also listed in Table 3. If loading rate effects are ignored, these moduli should be approximately equal. However, the results show that the modulus values determined from the repetitive tests are approximately 3 to 11 times greater than the static modulus values. This lack of agreement is possibly due to loading rate effects and differences in the strain measuring equipment; e.g., the repetitive test strains were measured with LVDT clamps, while the static tests used an externally mounted LVDT. Barker[3] has shown that considerably more strains (i.e., lower modulus values) are measured with externally mounted devices than LVDT clamps.

CONCLUSIONS

Based upon the material tested, the equipment and procedures used, the following conclusions are drawn:

a. The specimen stiffness, expressed as CBR or UCS, is dependent upon molding moisture content and density. Hence, properties dependent upon soil stiffness would be affected by compaction conditions.

b. The plastic axial strains increase with number and magnitude of axial stress repetitions. The relationship between the plastic axial strain and repetitive stress magnitude can be represented by a hyperbola and is dependent upon specimen stiffness.

c. The resilient modulus M_r initially tends to decrease with stress repetitions, followed in some cases by a gradual increase with continuing repetitions. The resilient modulus is also a function of the deviator stress, specimen stiffness, and to a lesser extent confining pressure.

d. The relationship between resilient and plastic strain is dependent upon soil stiffness.

e. Up to 70 percent of the static UCS, the magnitude of the axial stress during conditioning has little effect on subsequent resilient modulus values.

f. Poisson's ratio for the conditions tested was insensitive to number and magnitude of axial stress repetitions, confining pressure, and specimen stiffness.

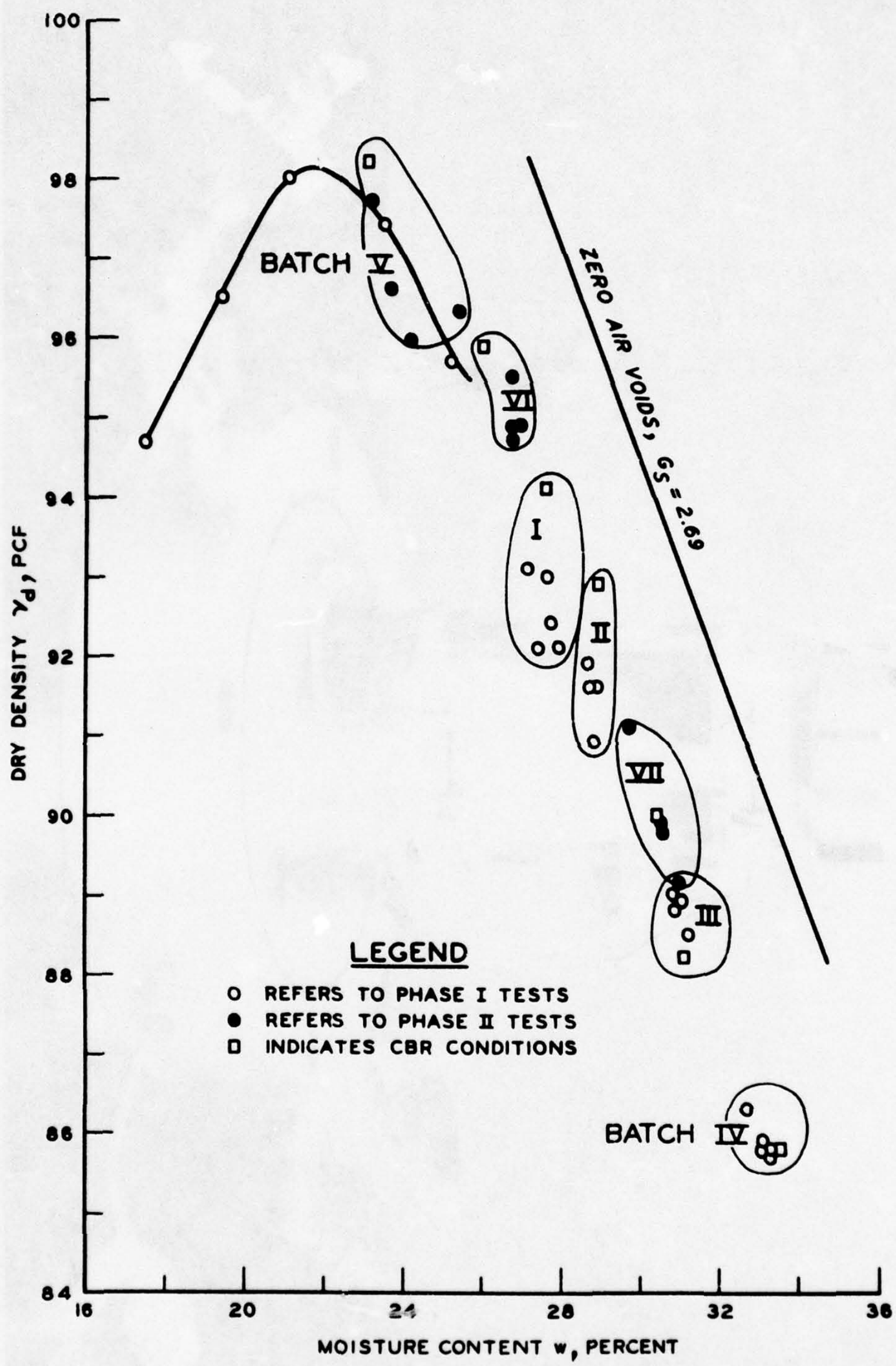

Figure 1. Compaction curve for heavy clay and conditions for various test batches

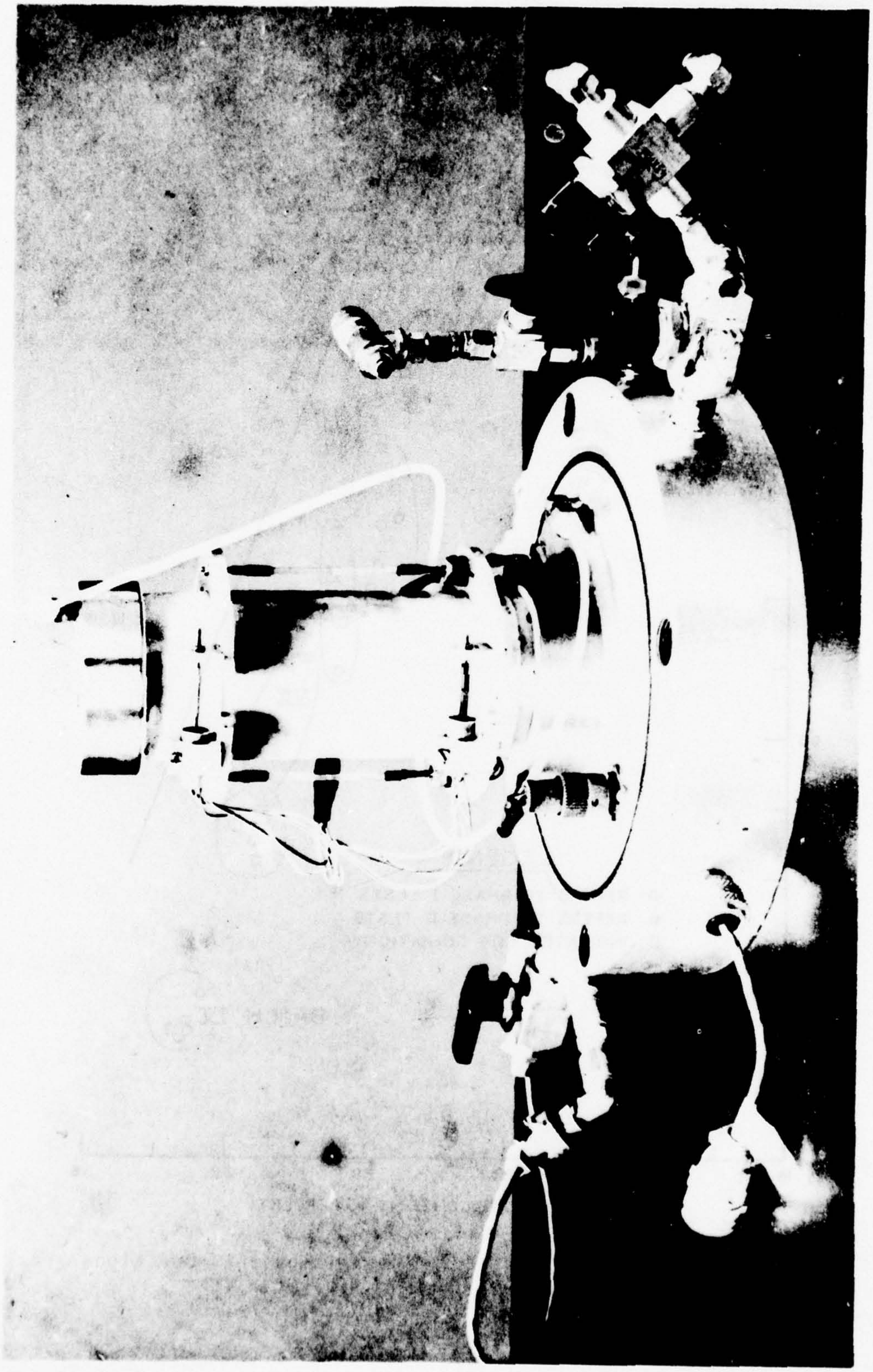

Figure 2. Specimen with the LVDT clamps ready for testing in the chamber

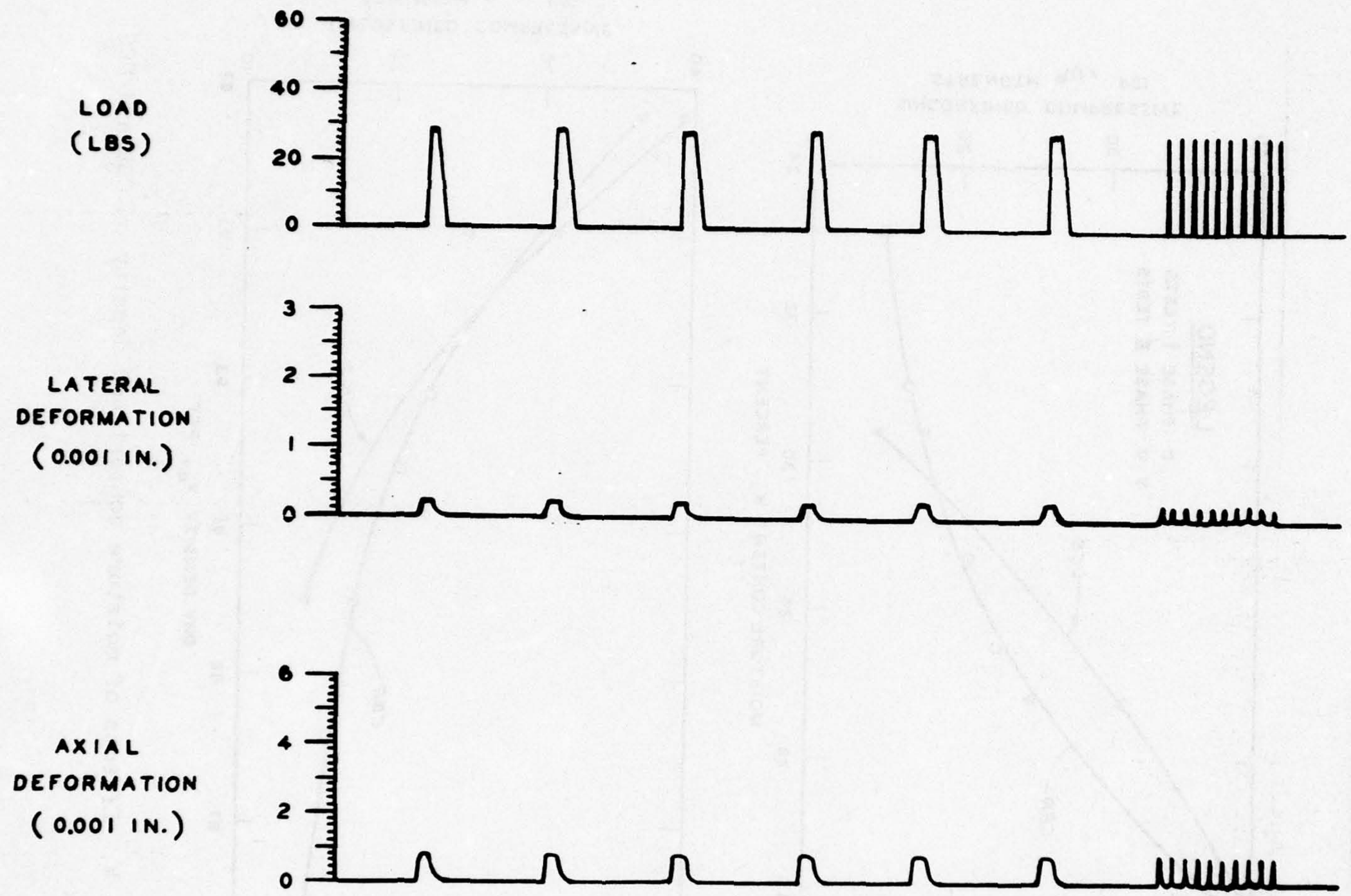

Figure 3. Typical recordings of load, axial and radial determinations for Phase II tests

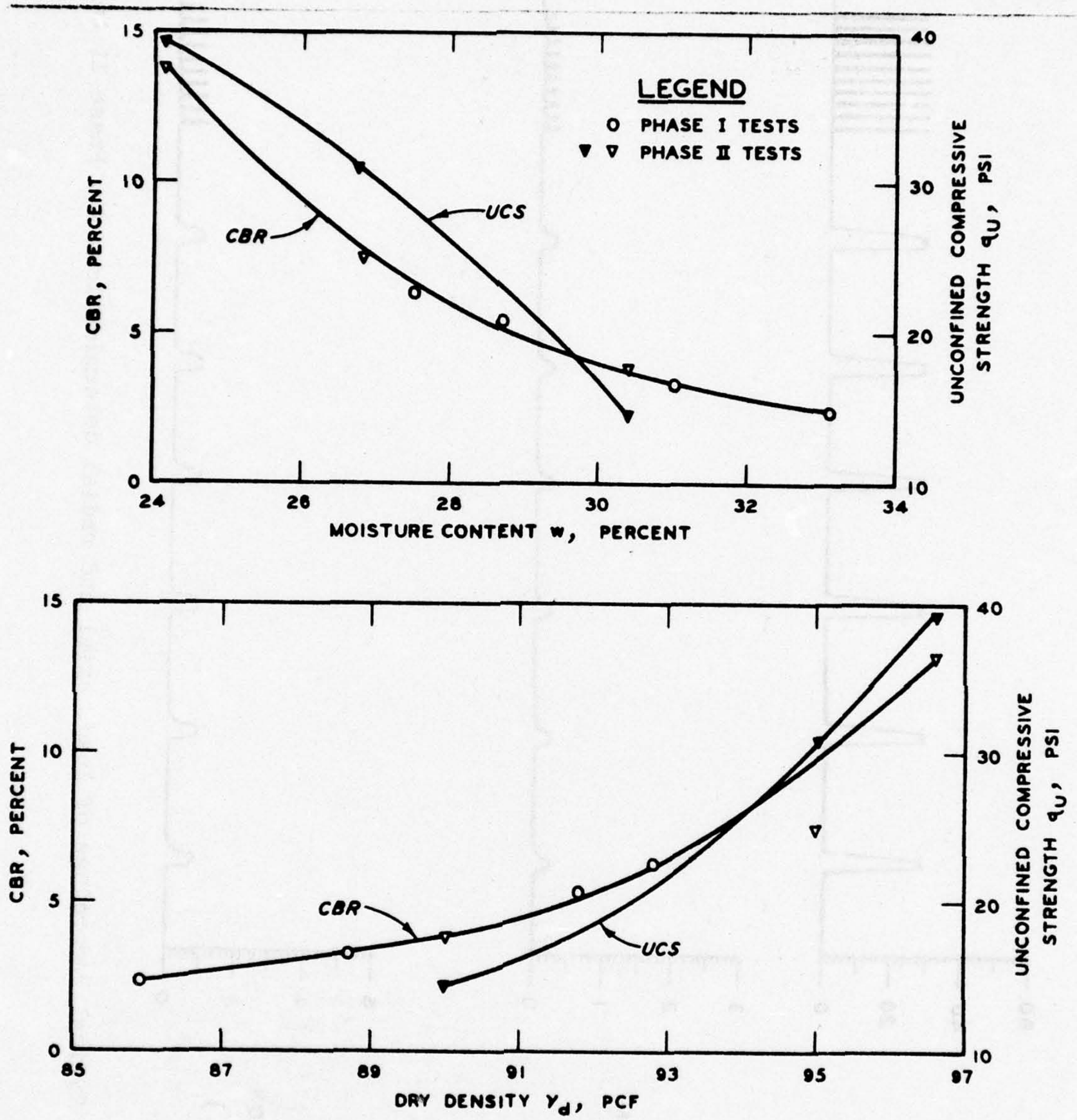

Figure 4. Effects of moisture content and density on CBR and UCS

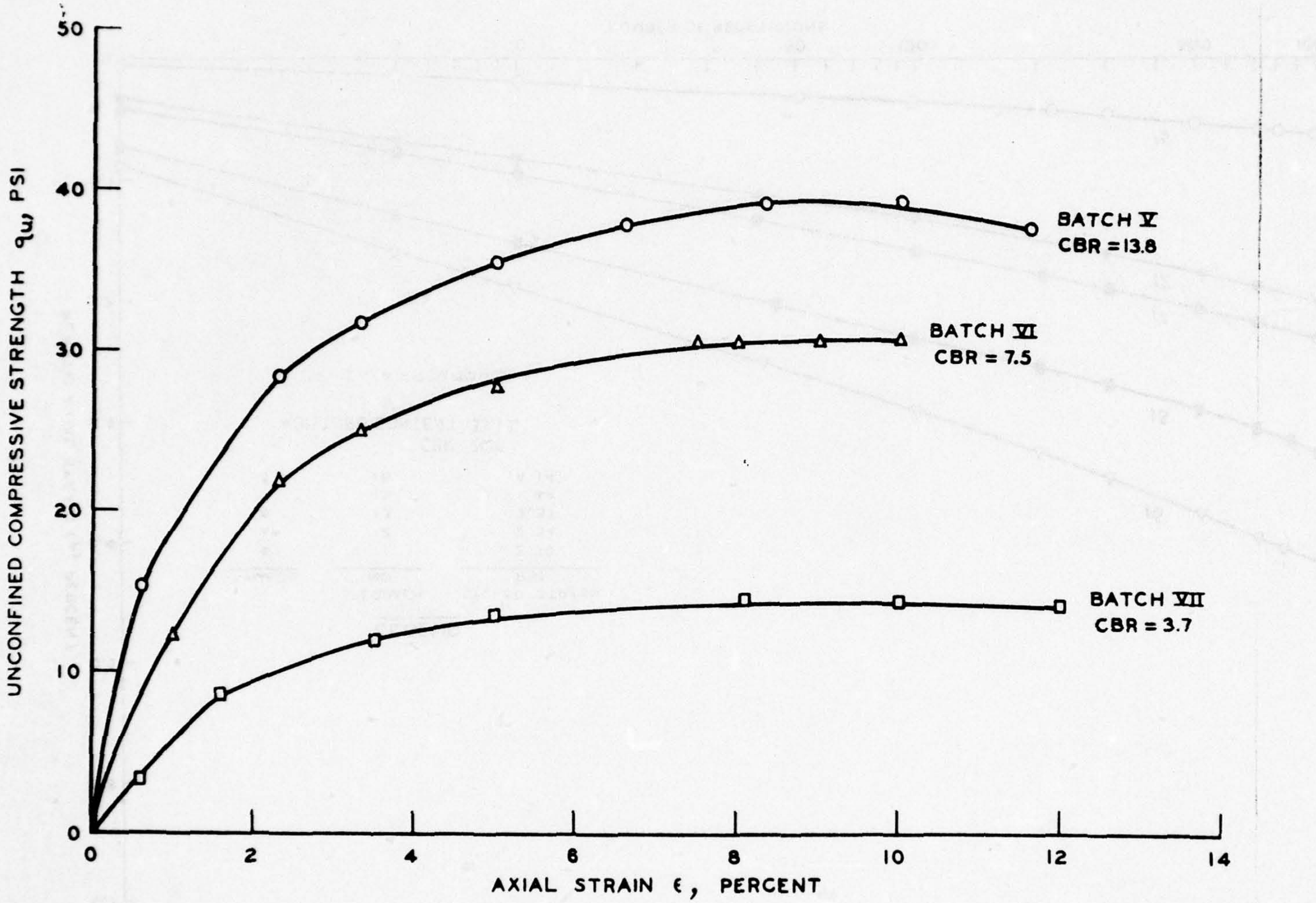

Figure 5. Stress-strain relationships for unconfined compression tests on heavy clay

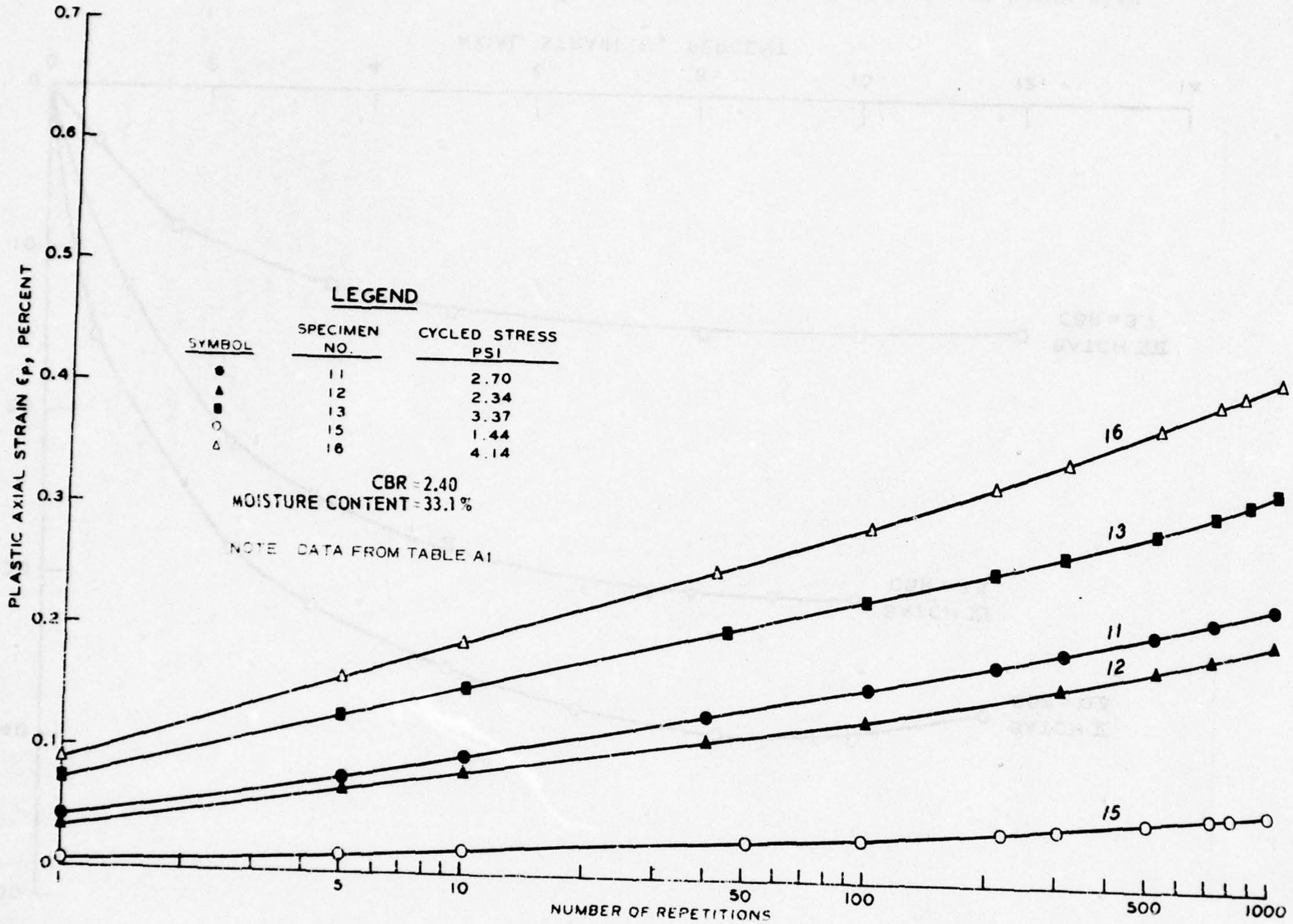

Figure 6. Effect of number of repetitions on plastic axial strain for CBR = 2.4 , Phase I tests

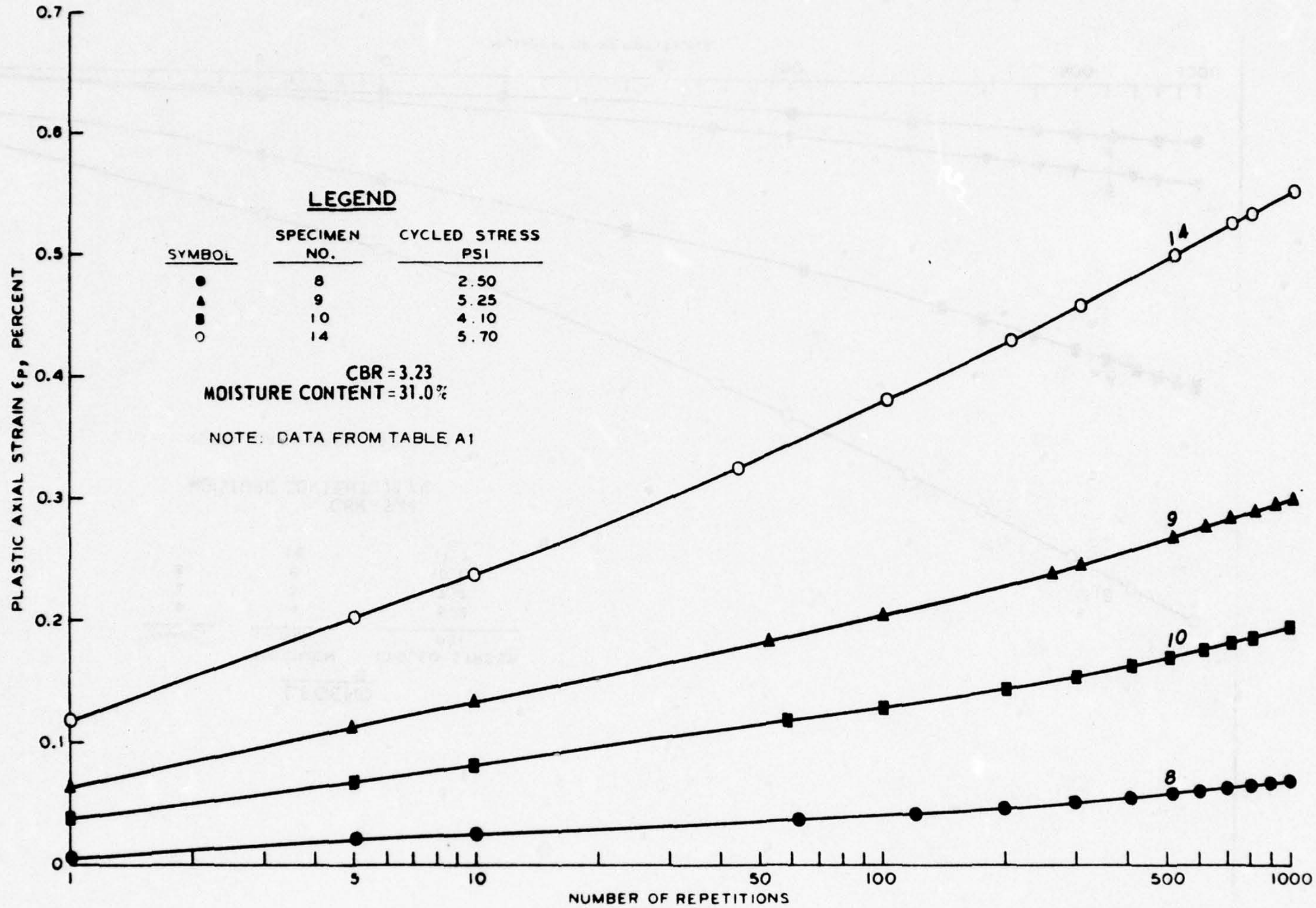

Figure 7. Effect of number of repetitions on plastic axial strain for CBR = 3.23 , Phase I tests

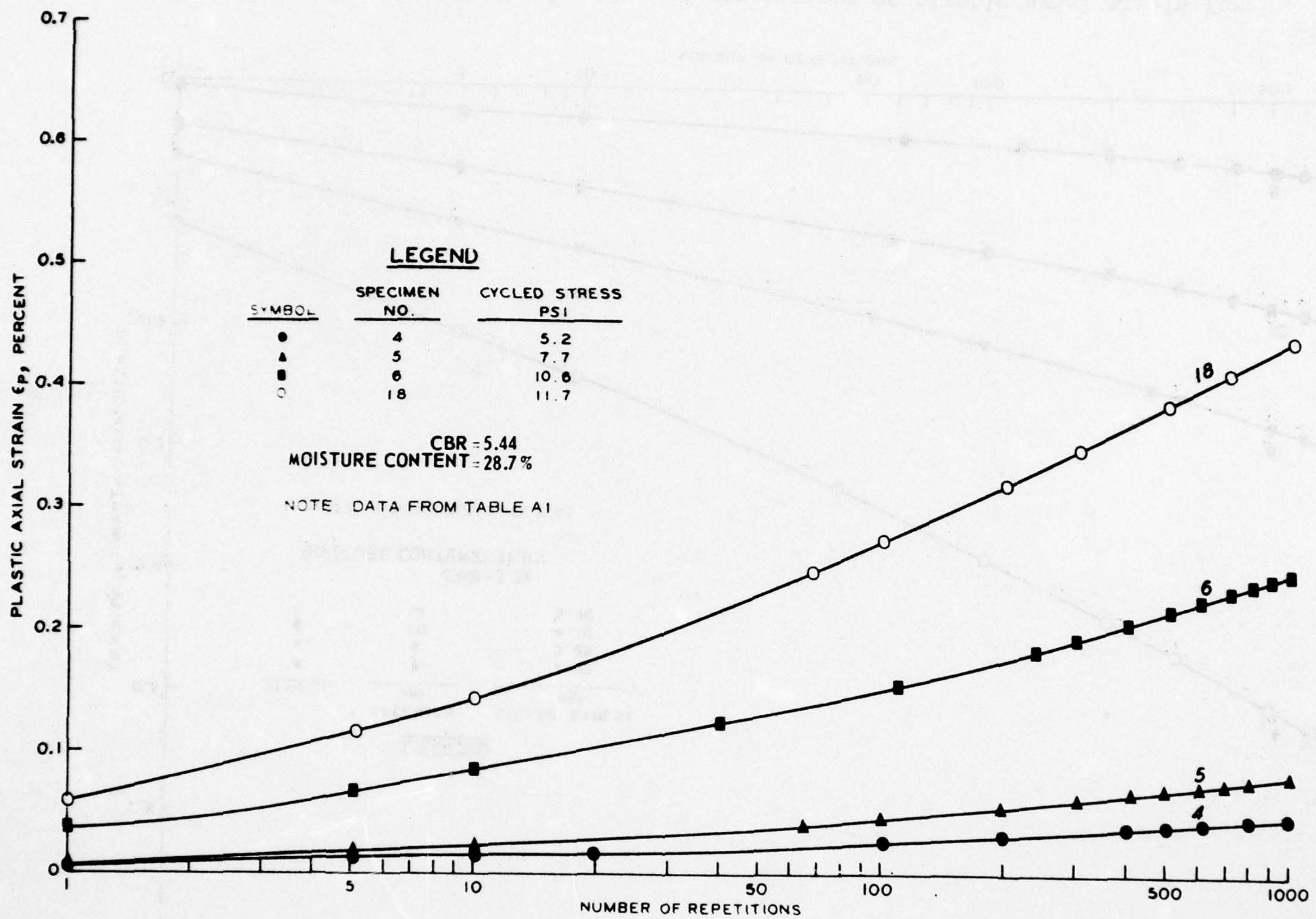

Figure 8. Effect of number of repetitions on plastic axial strain for CBR = 5.44 , Phase I tests

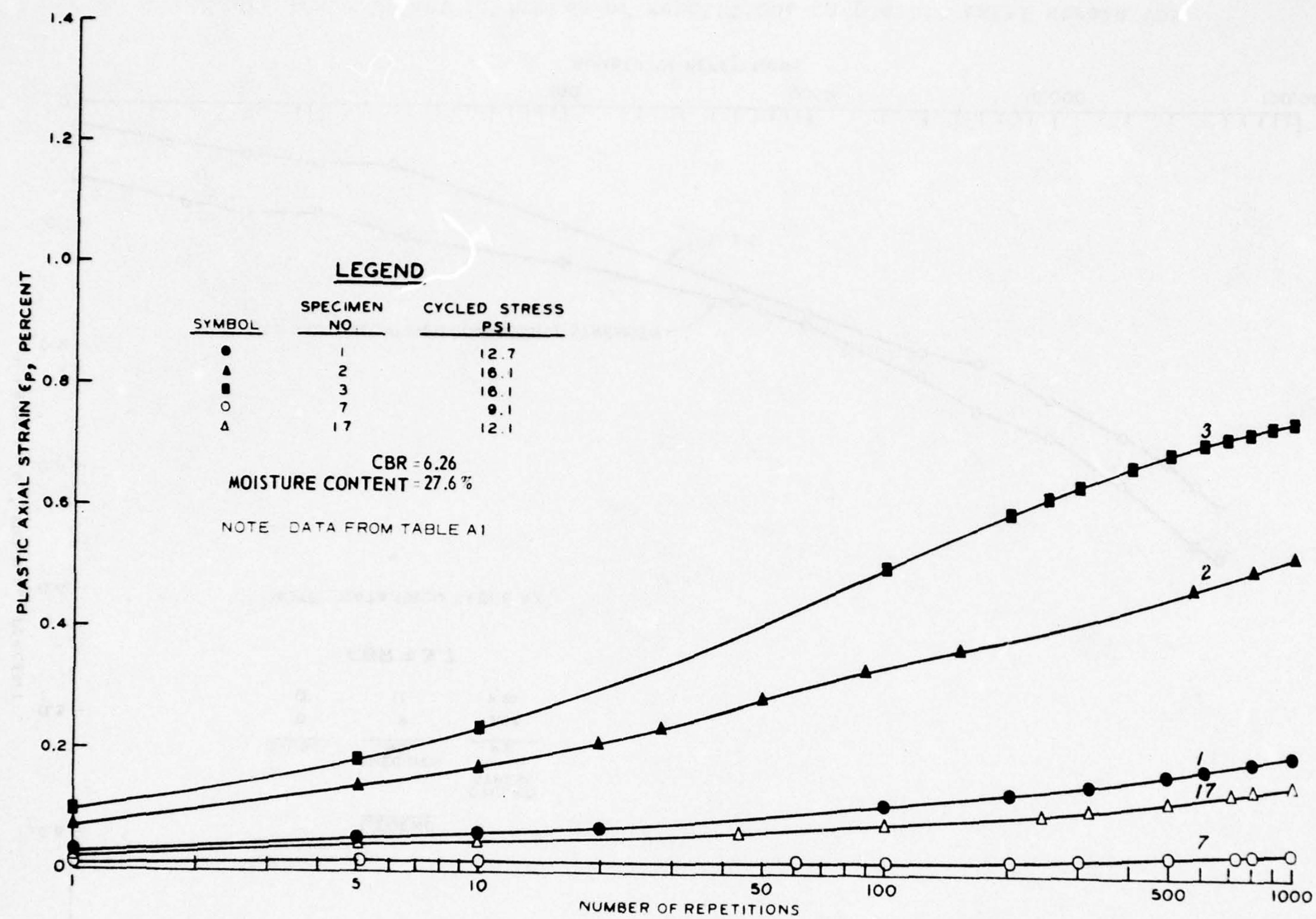

Figure 9. Effect of number of repetitions on plastic axial strain for CBR = 6.26 , Phase I tests

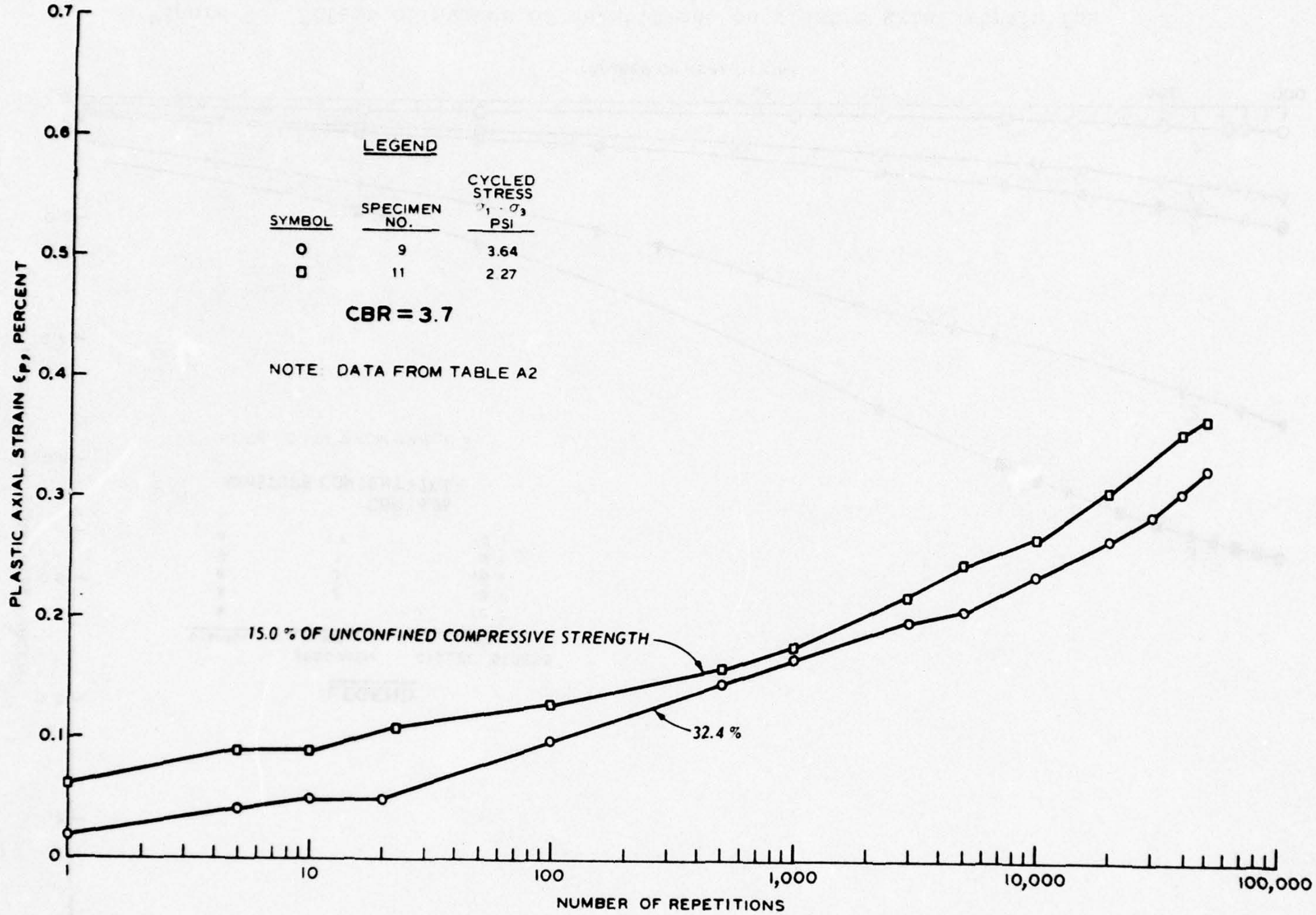

Figure 10a. Effect of number of repetitions on plastic axial strain for CBR = 3.7 , Phase II tests

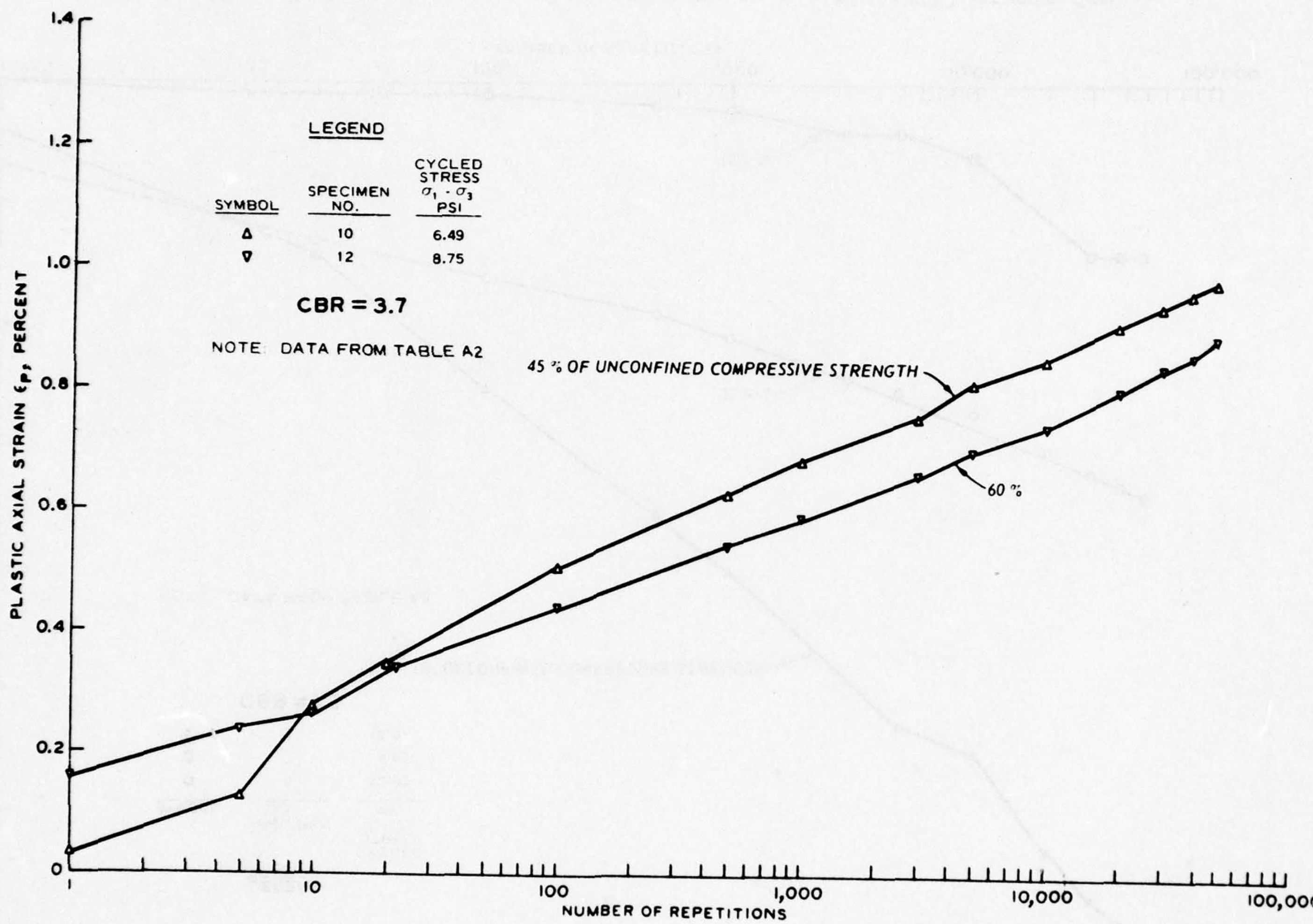

Figure 10b. Effect of number of repetitions on plastic axial strain for CBR = 3.7 , Phase II tests

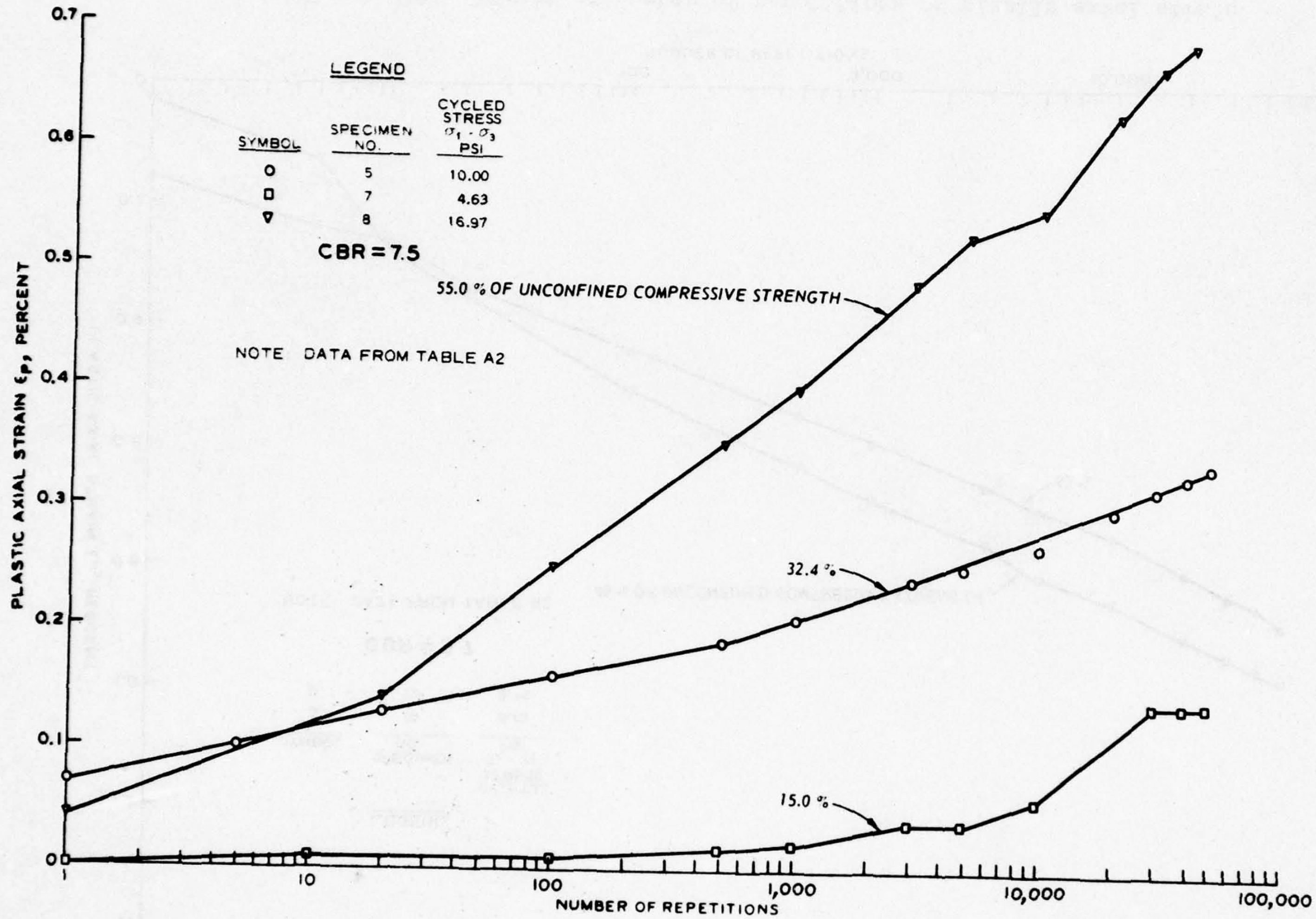

Figure 11a. Effect of number of repetitions on plastic axial strain for CBR = 7.5 , Phase II tests

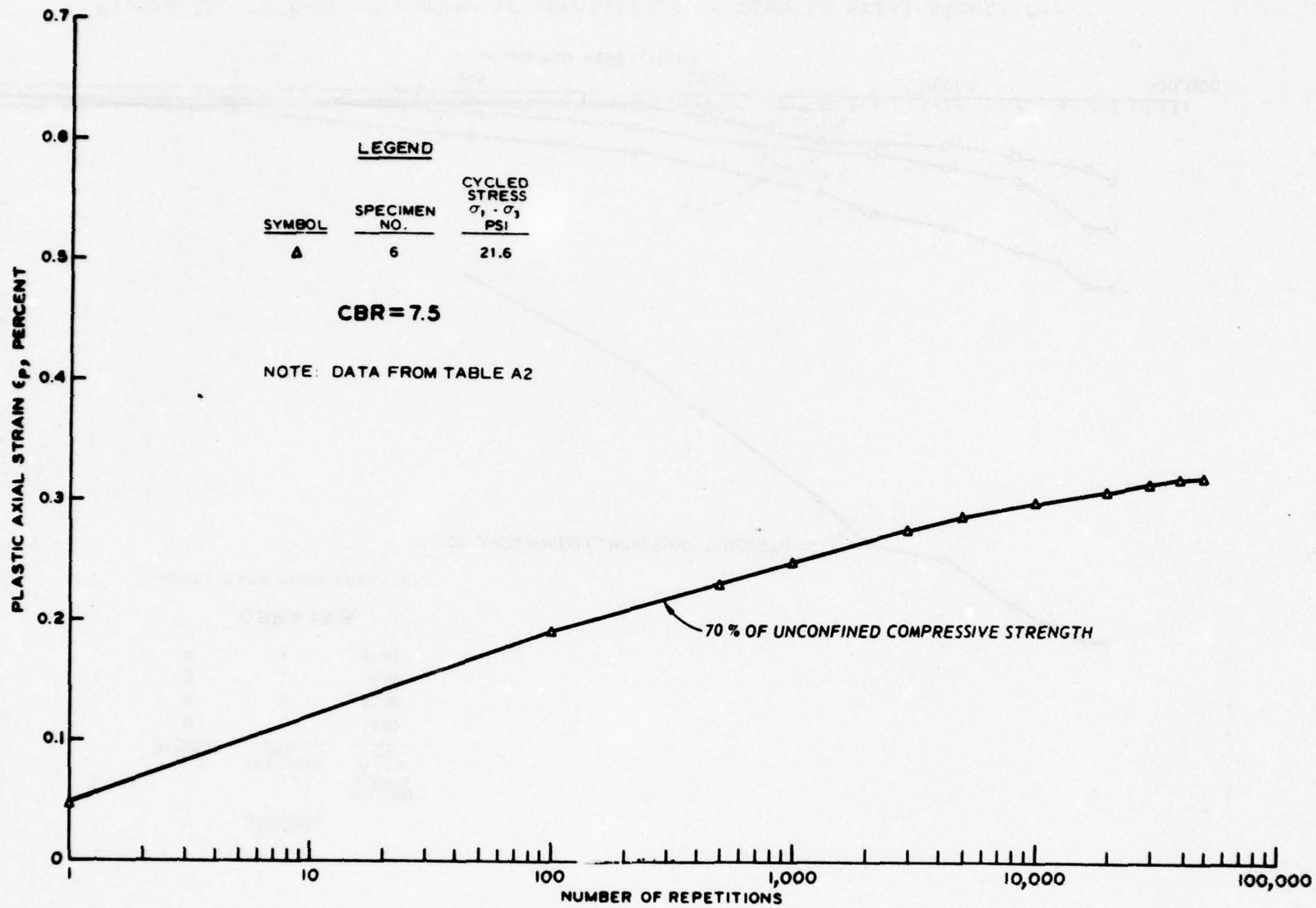

Figure 11b. Effect of number of repetitions on plastic axial strain for CBR = 7.5 , Phase II tests

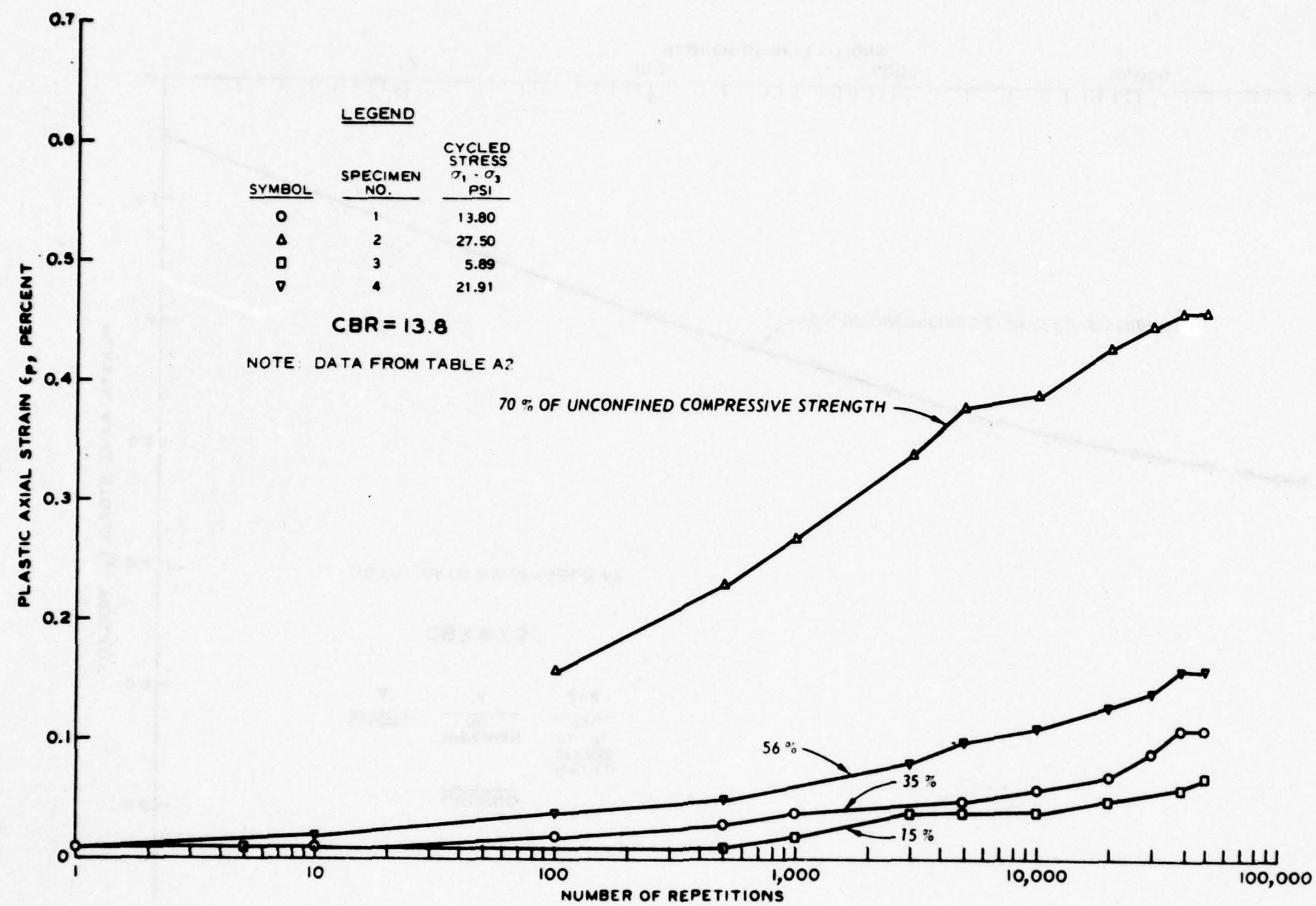

Figure 12. Effect of number of repetitions on plastic axial strain for CBR = 13.8 , Phase II tests

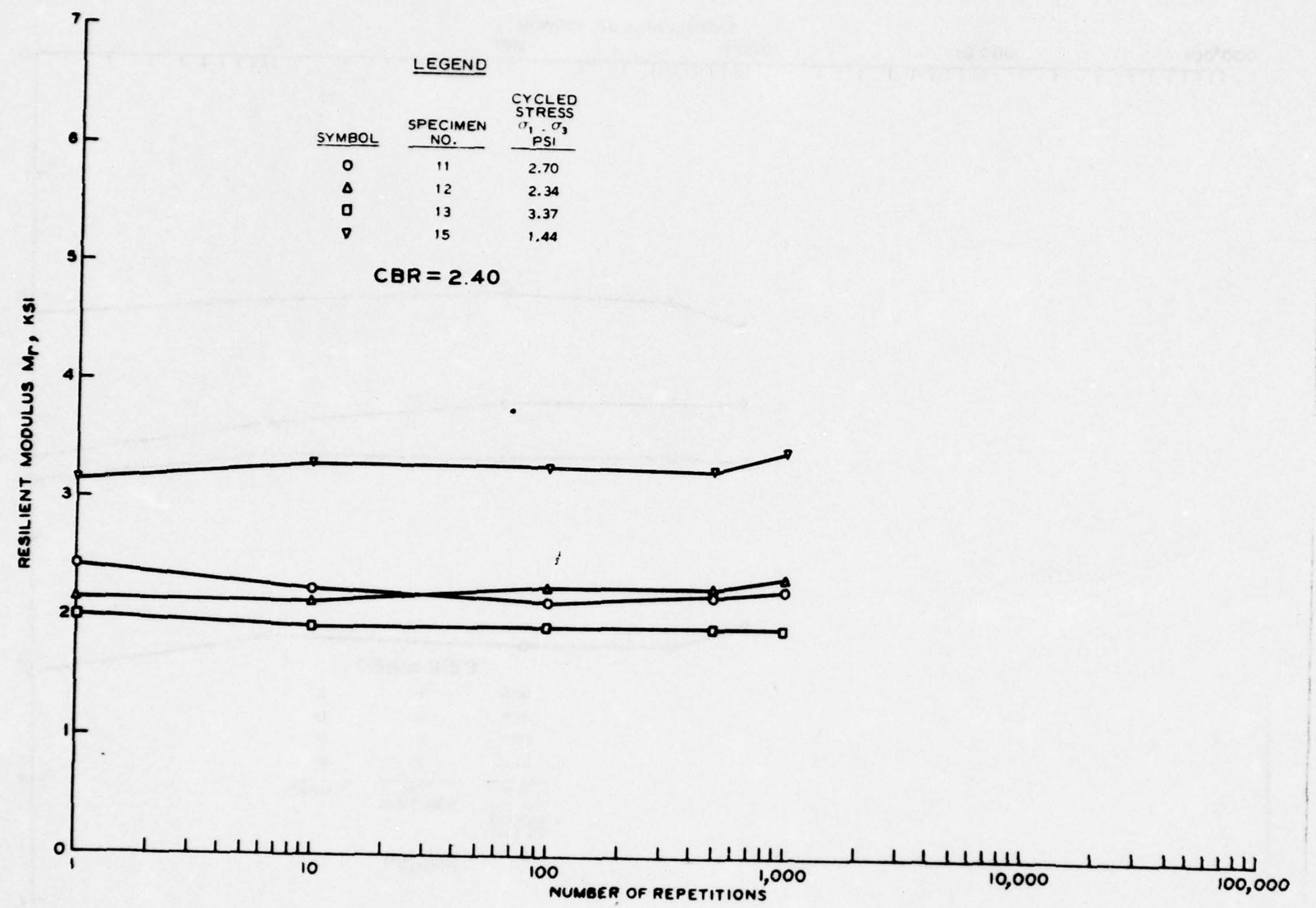

Figure 13. Resilient modulus versus number of load repetitions for CBR = 2.4 , Phase I tests

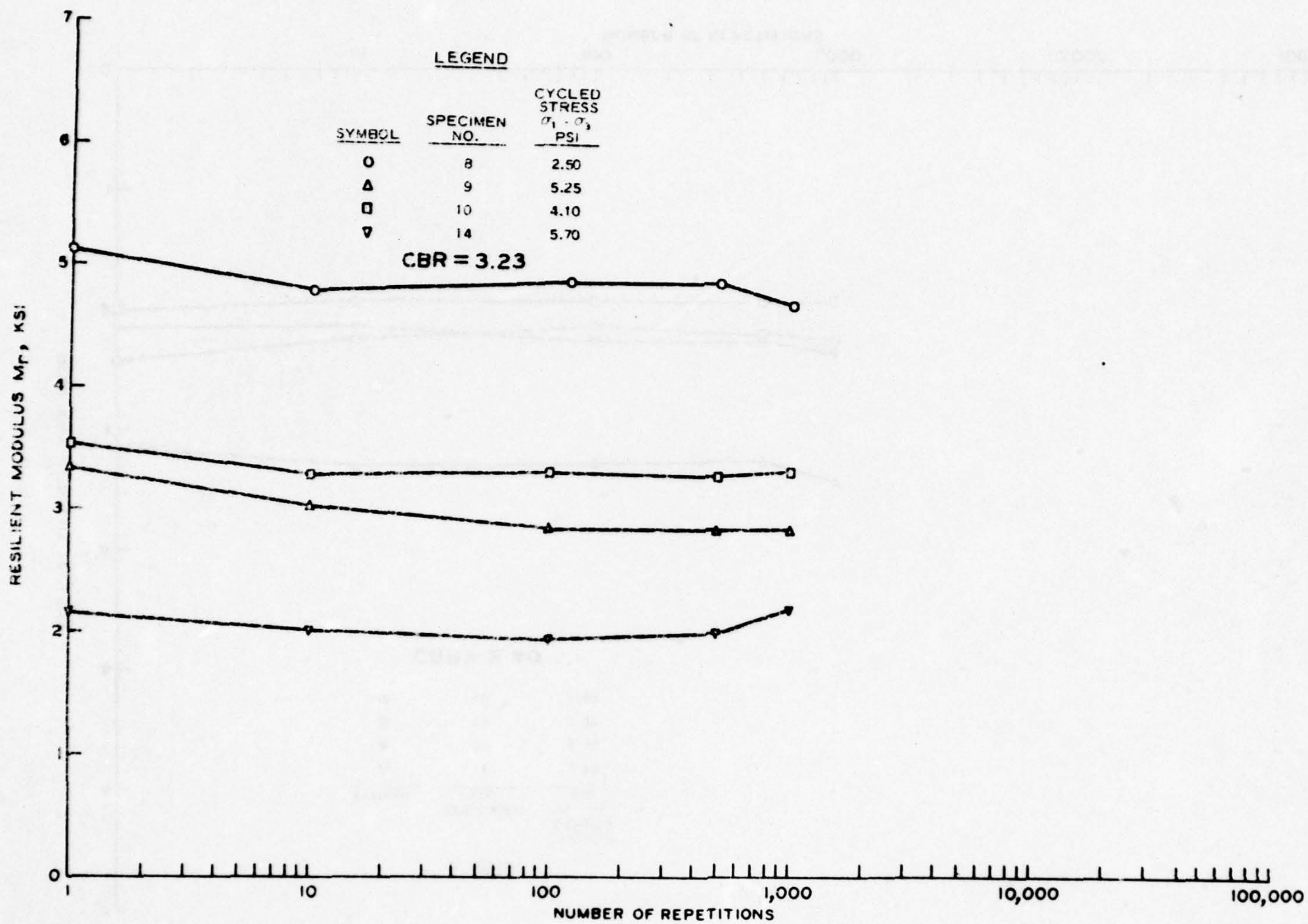

Figure 14. Resilient modulus versus number of load repetitions for CBR = 3.23 , Phase I tests

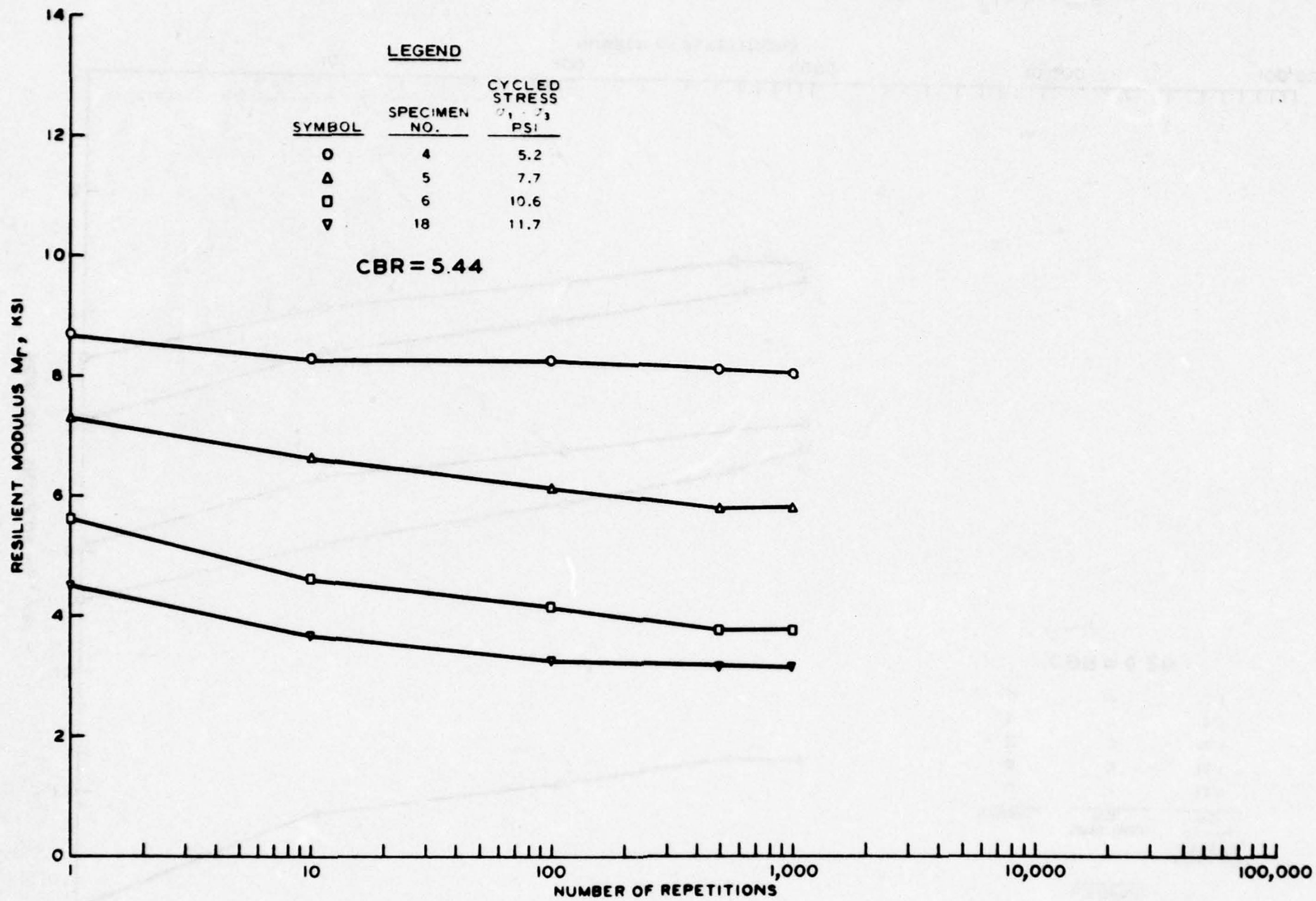

Figure 15. Resilient modulus versus number of load repetitions for CBR = 5.44 , Phase I tests

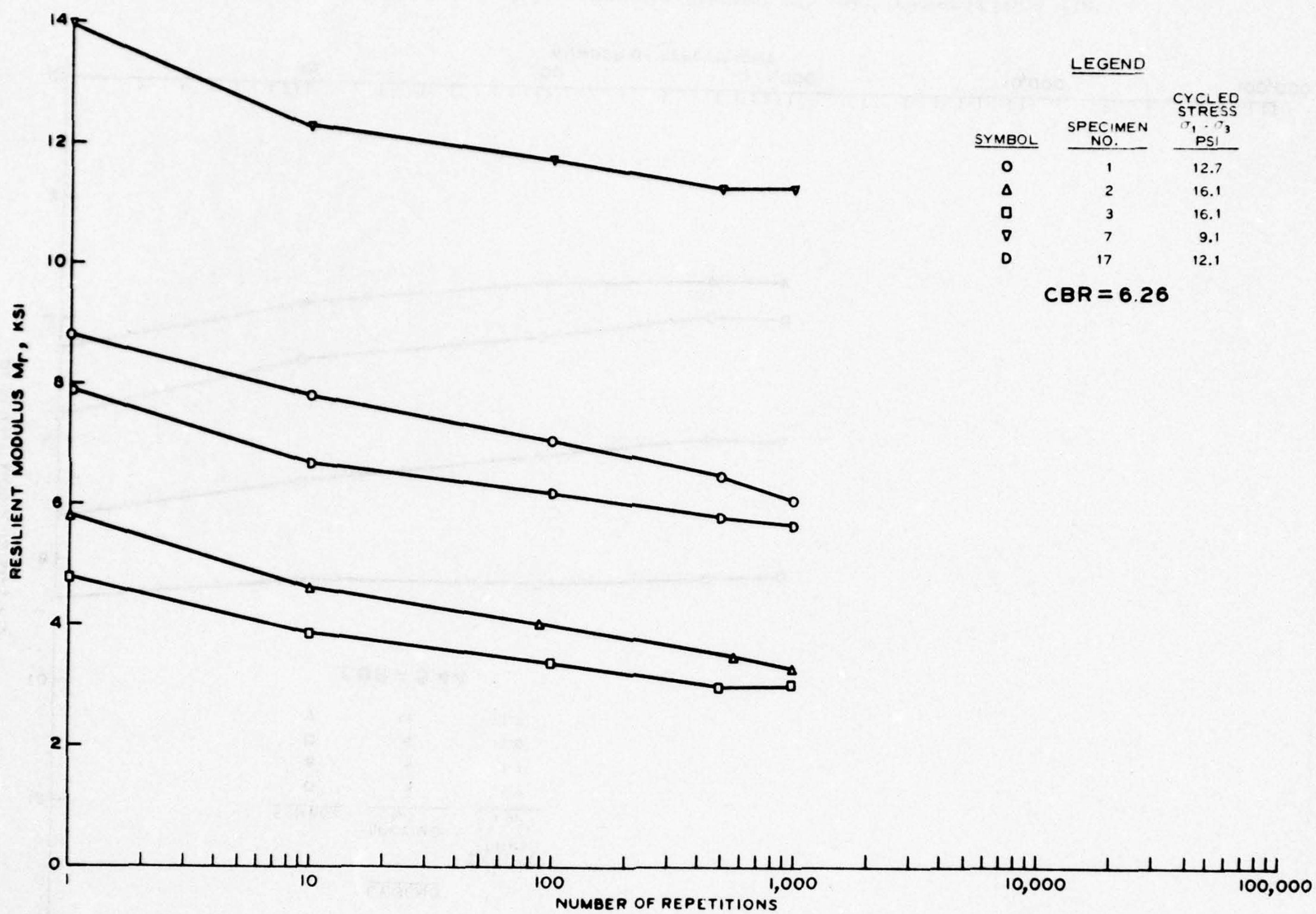

Figure 16. Resilient modulus versus number of load repetitions for CBR = 6.26 , Phase I tests

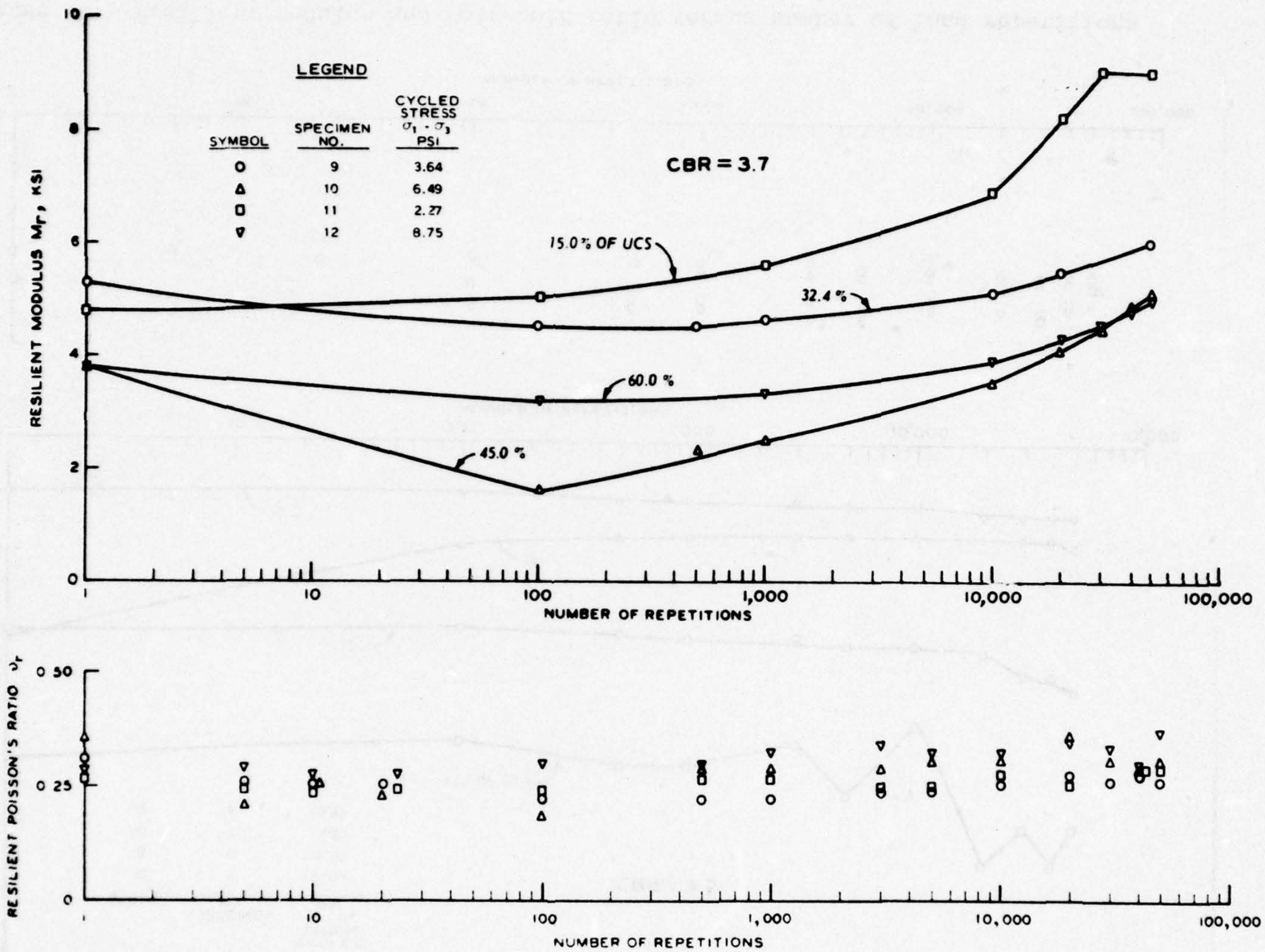

Figure 17. Resilient modulus and Poisson's ratio versus number of load repetitions for CBR = 3.7 , Phase II tests

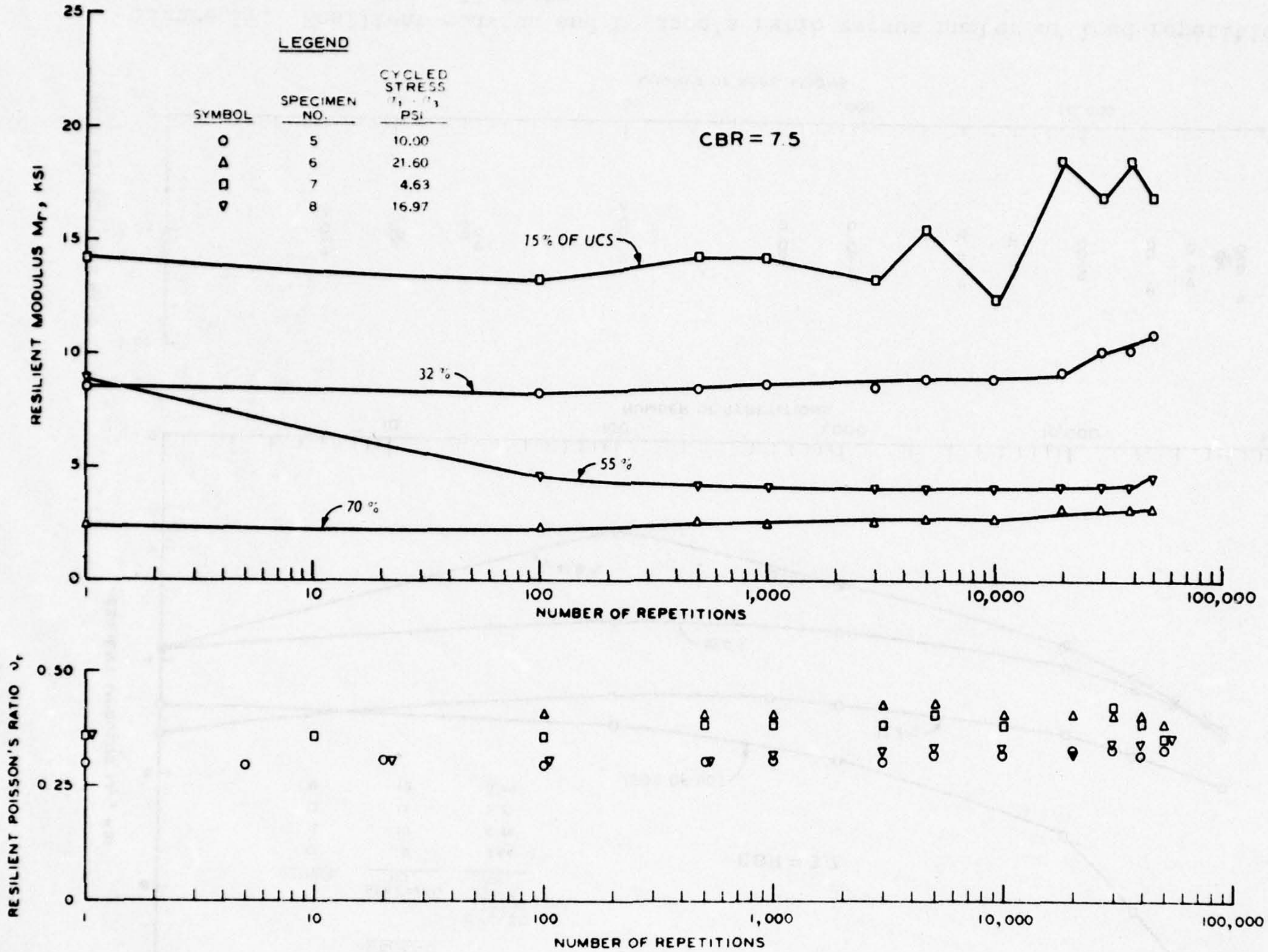

Figure 18. Resilient modulus and Poisson's ratio versus number of load repetitions for CBR = 7.5 , Phase II tests

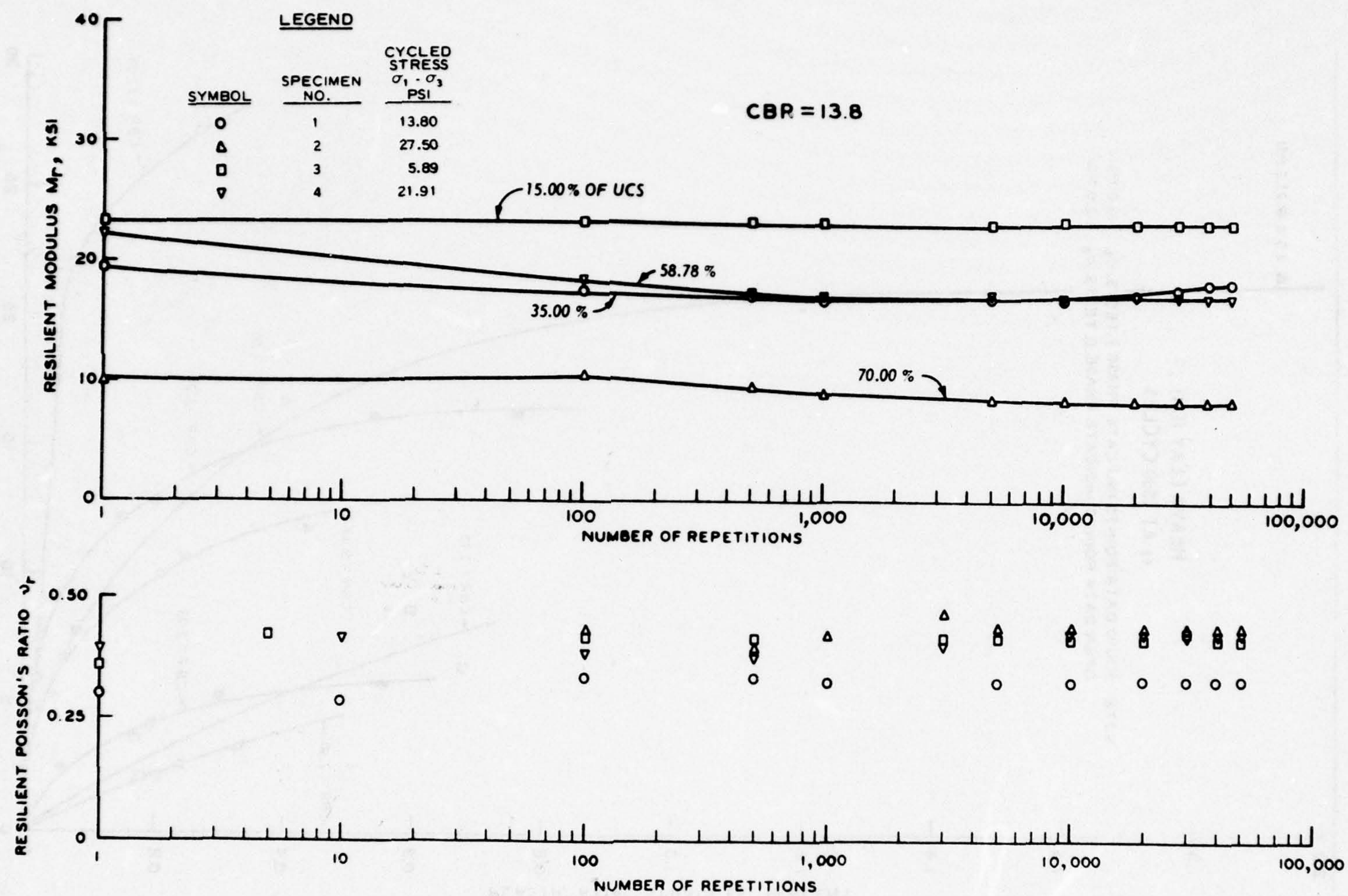

Figure 19. Resilient modulus and Poisson's ratio versus number of load repetitions for CBR = 13.8 , Phase II tests

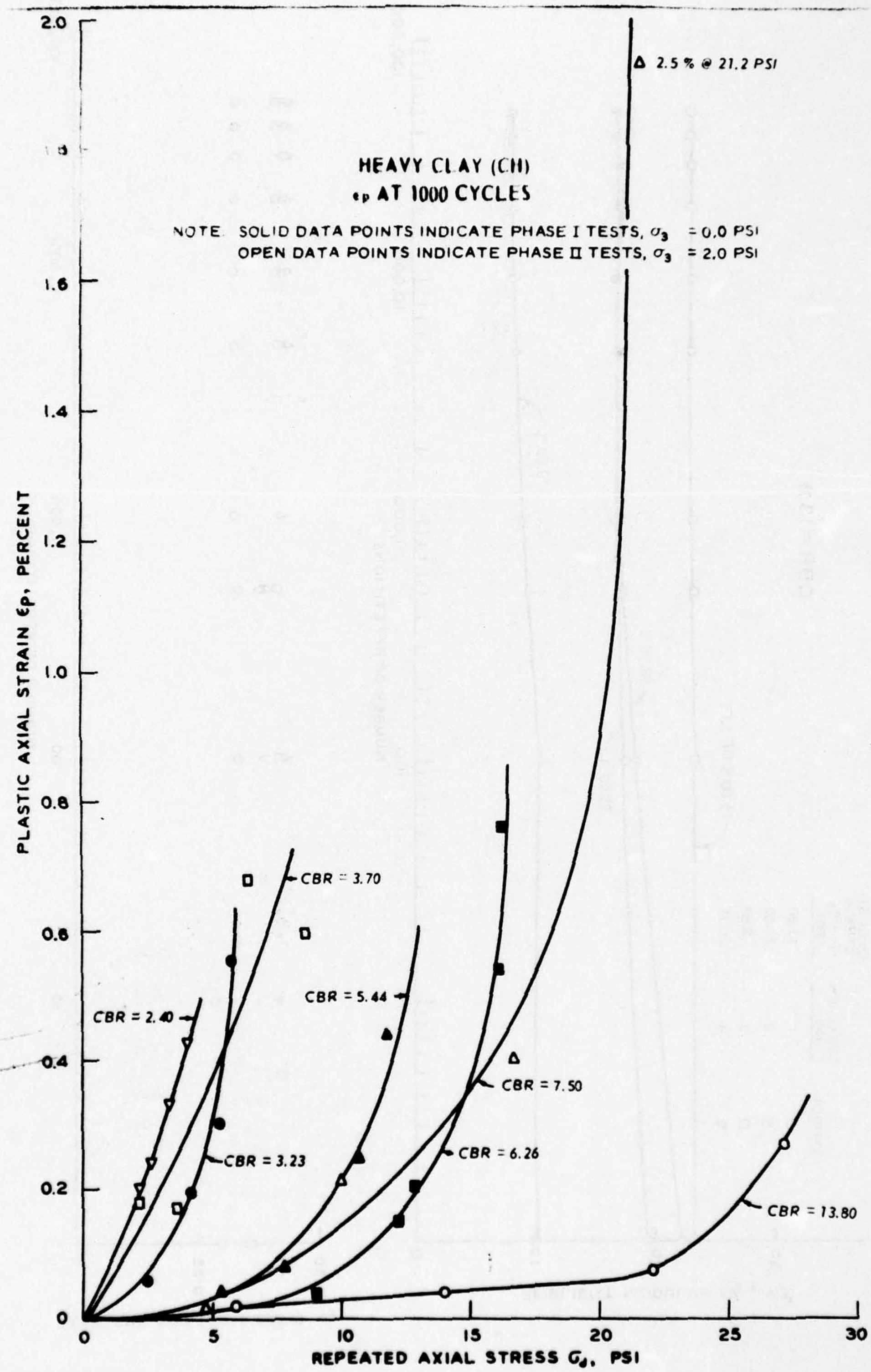

Figure 20. Relationship between plastic axial strain after 1000 repetitions and repeated axial stress

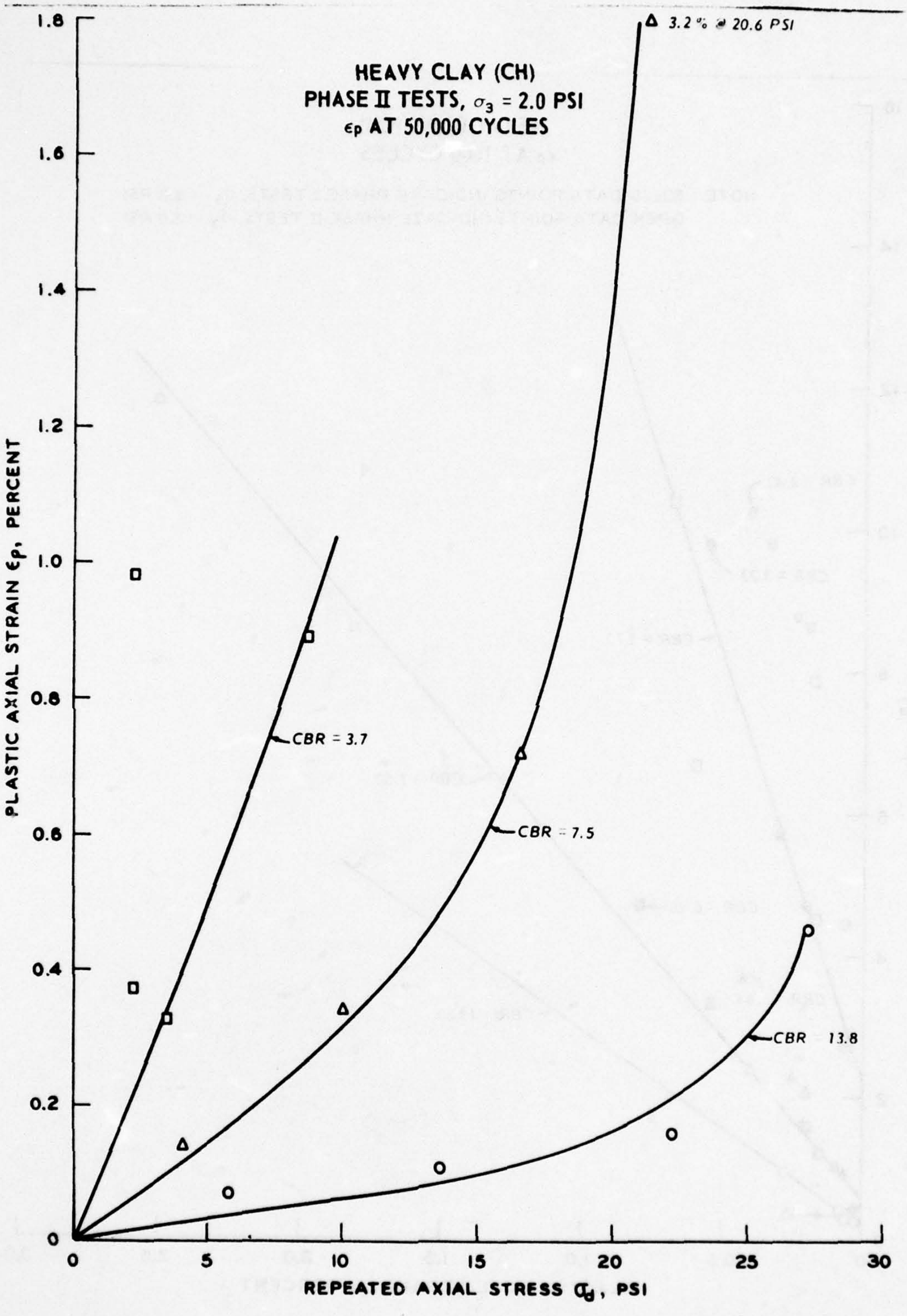

Figure 21. Relationship between plastic axial strain after 50,000 repetitions and repeated axial stress

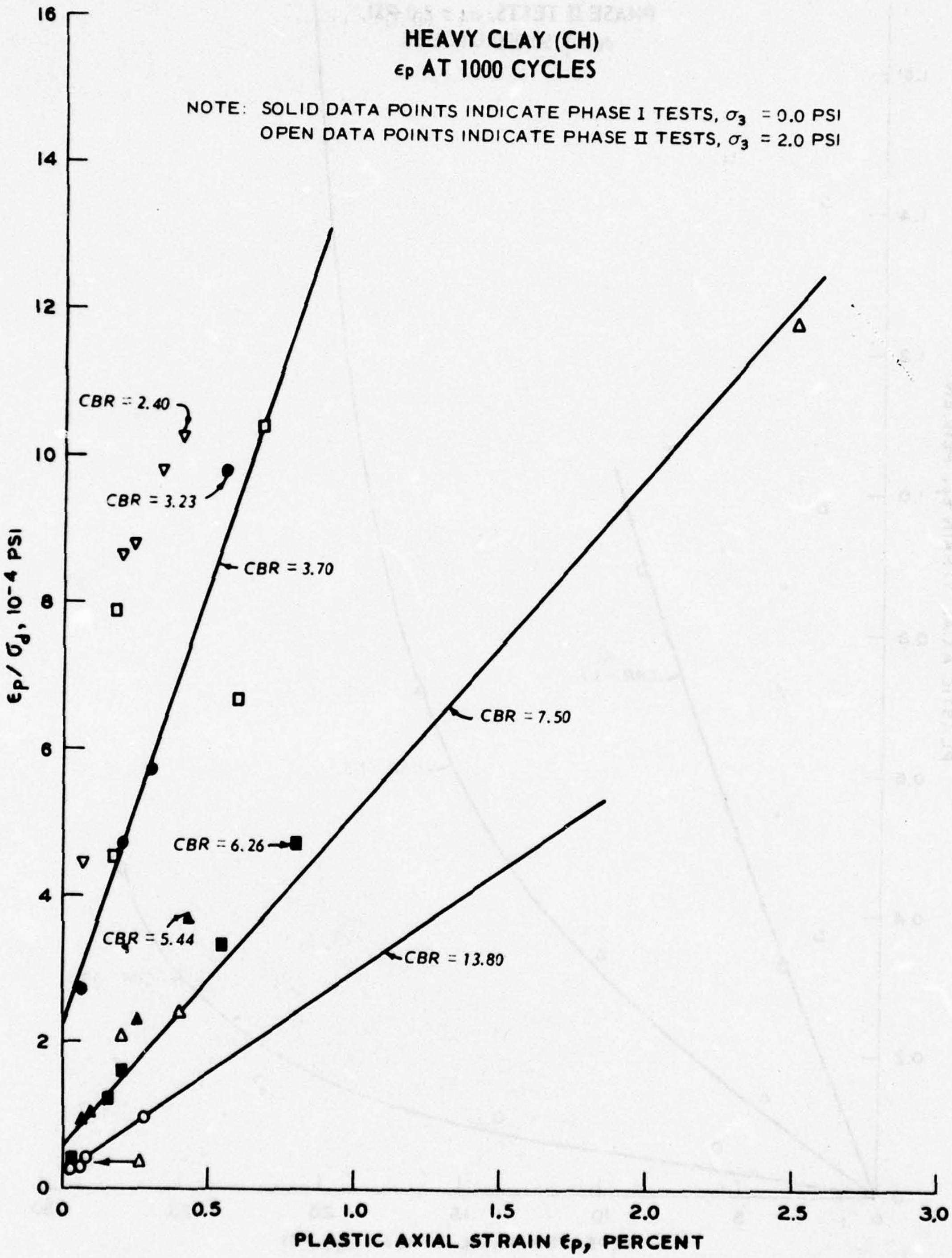

Figure 22. Hyperbolic relationships between plastic axial strain and repeated axial stress at 1000 repetitions

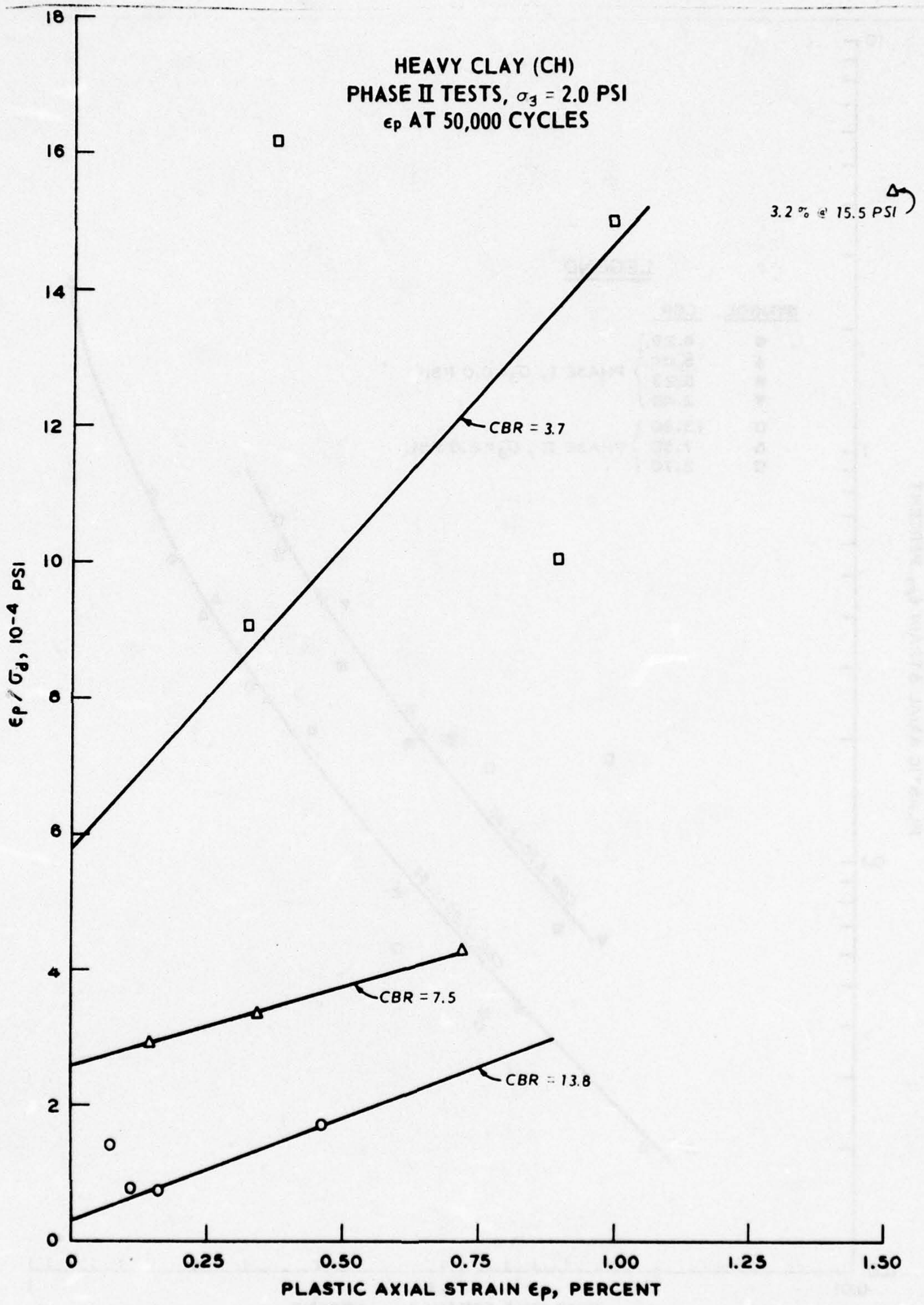

Figure 23. Hyperbolic relationships between plastic axial strain and repeated axial stress at 50,000 repetitions

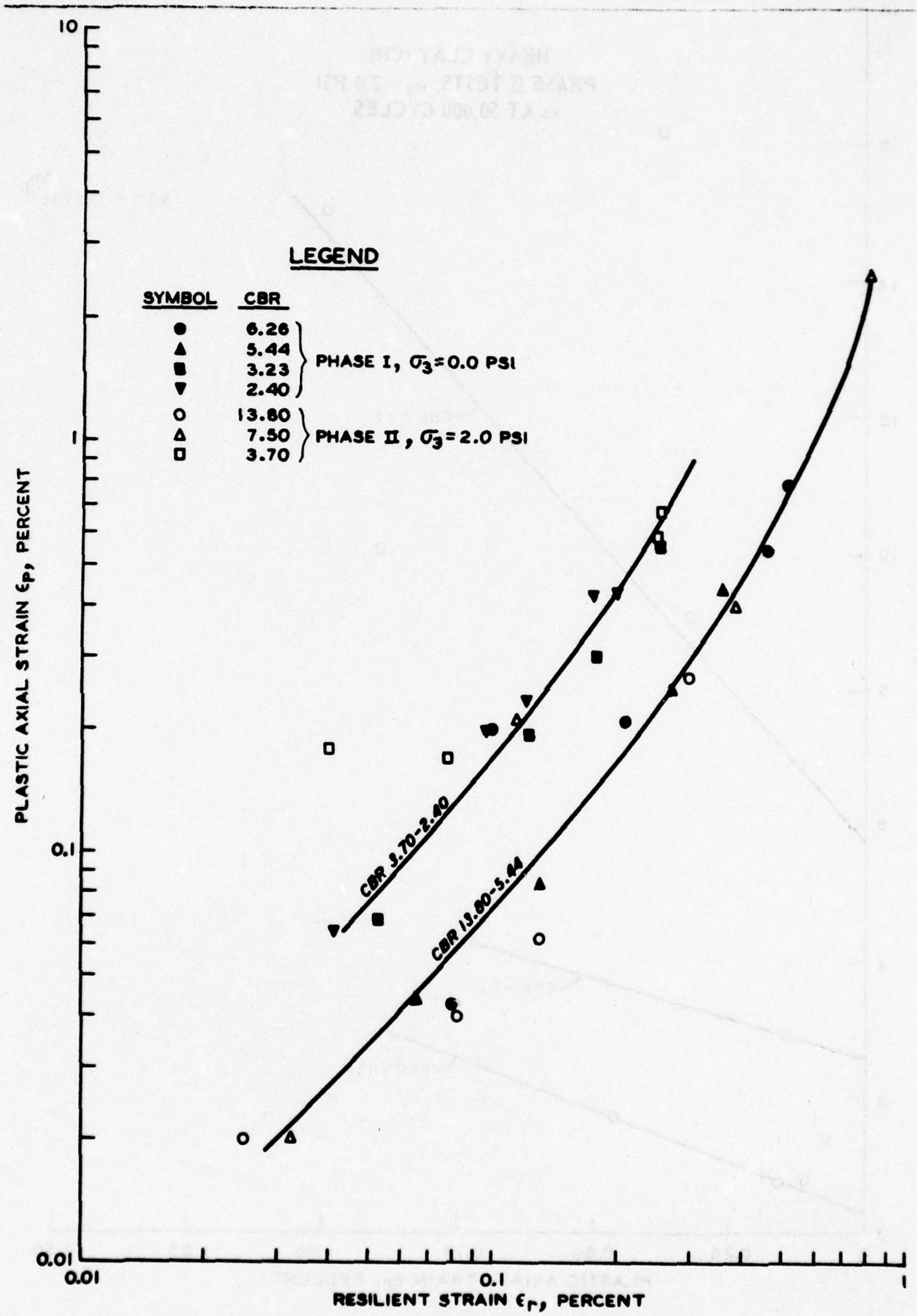

Figure 24. Relationship between plastic strain and resilient strain for heavy clay at 1000 repetitions

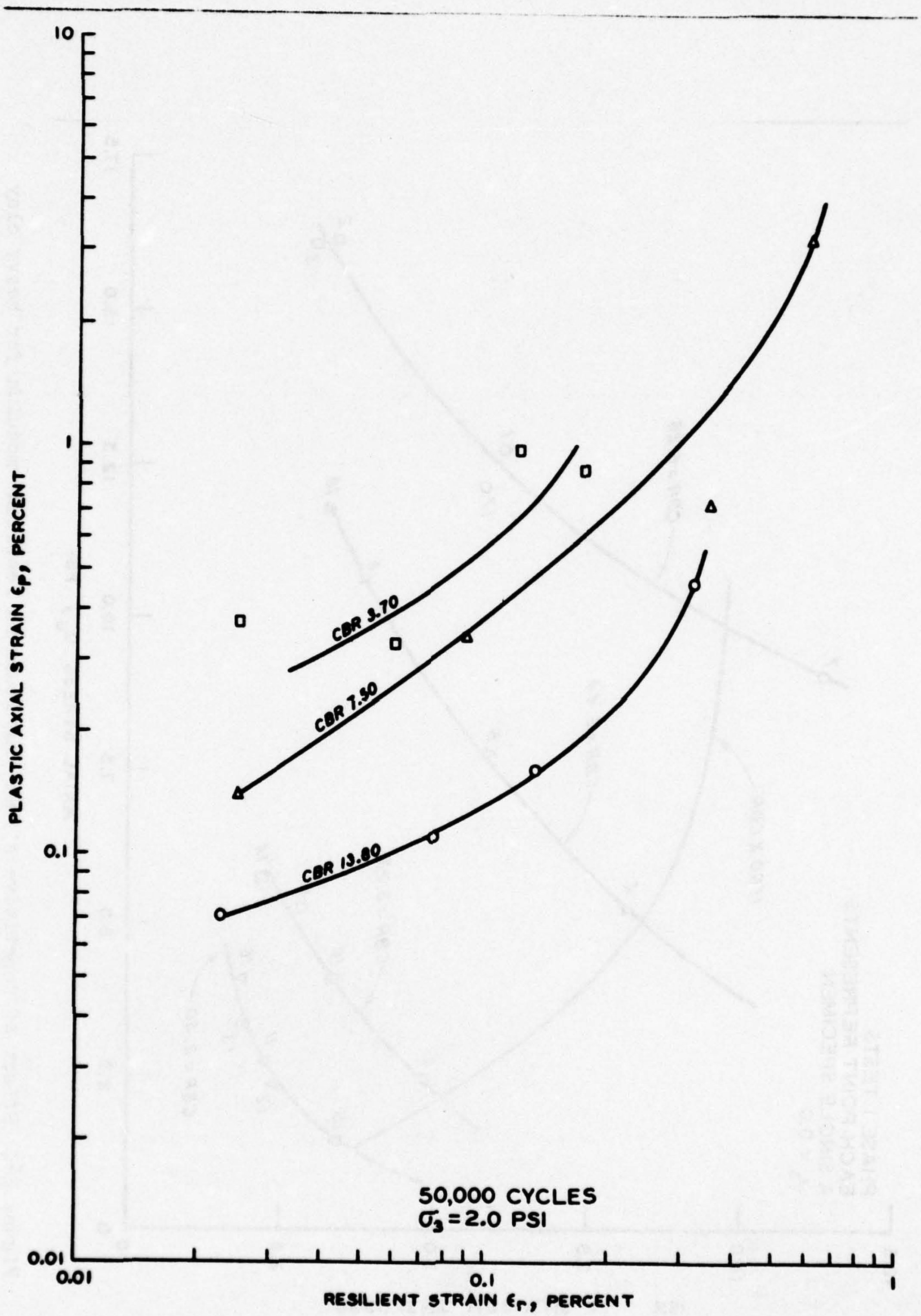

Figure 25. Relationship between plastic strain and resilient strain for heavy clay at 50,000 repetitions

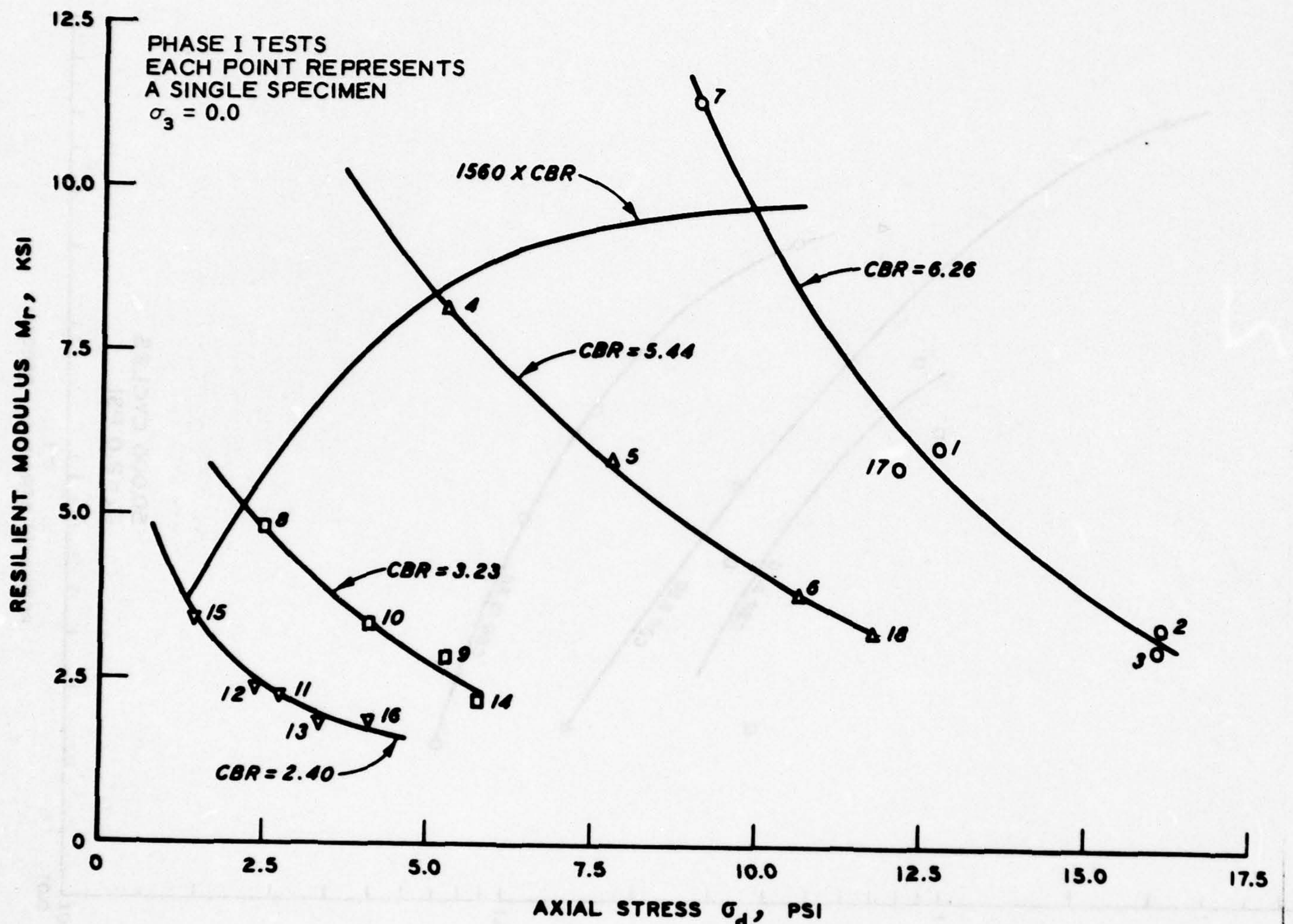

Figure 26. Effect of repetitive stress magnitude on resilient modulus for heavy clay

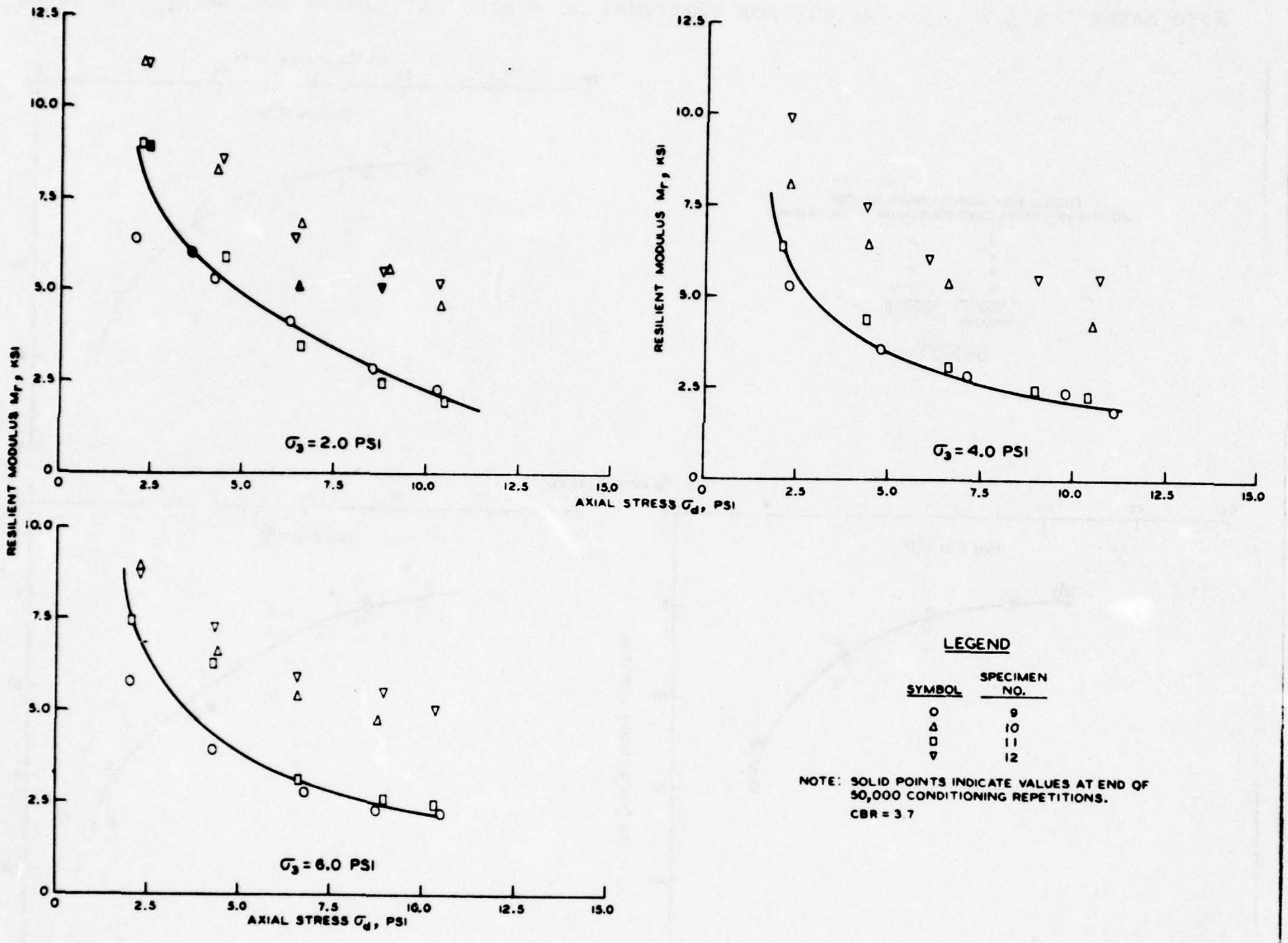

Figure 27. Effect of repetitive stress on resilient modulus for CBR = 3.7 , heavy clay

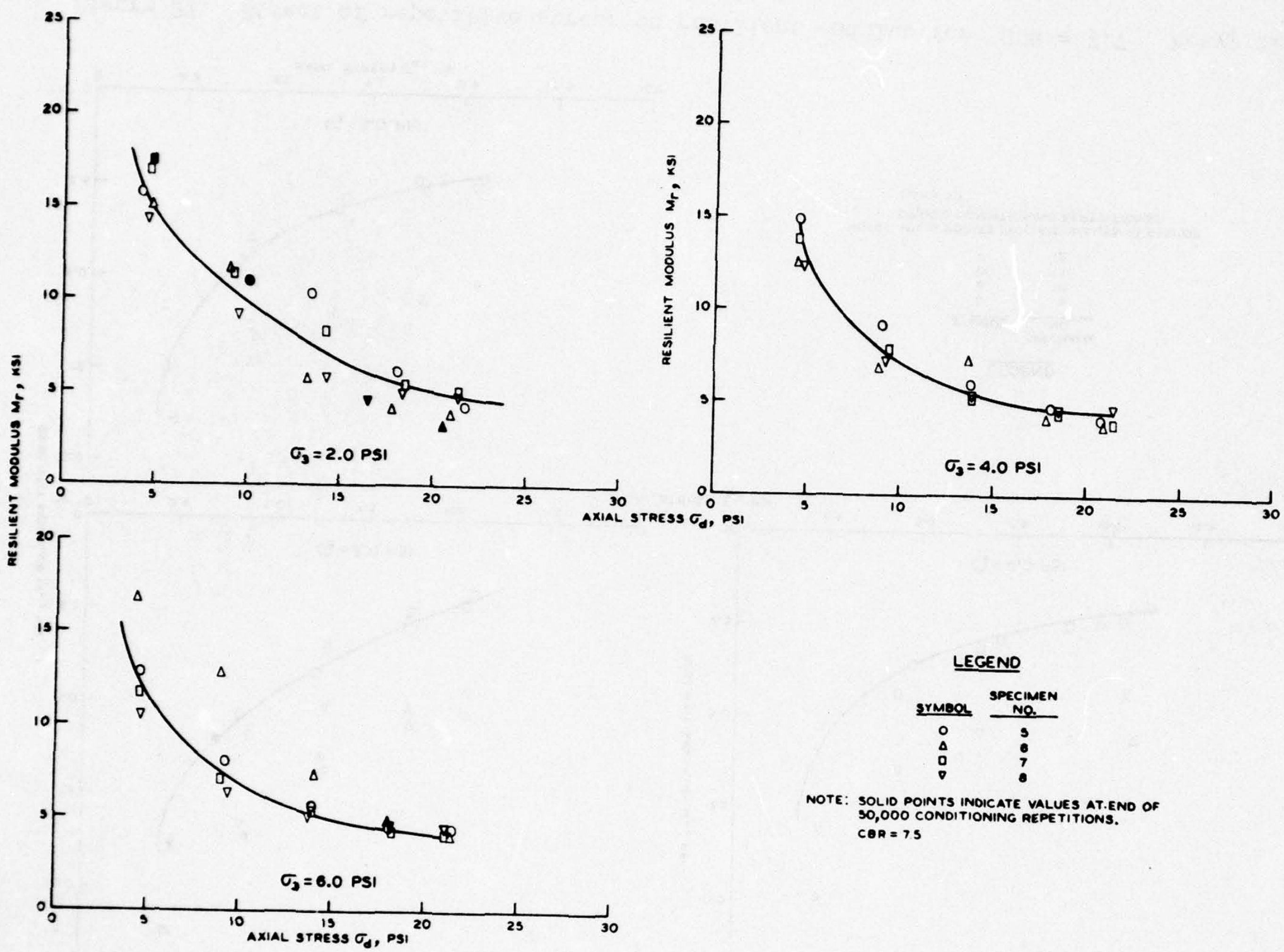

Figure 28. Effect of repetitive stress on resilient modulus for CBR = 7.5 , heavy clay

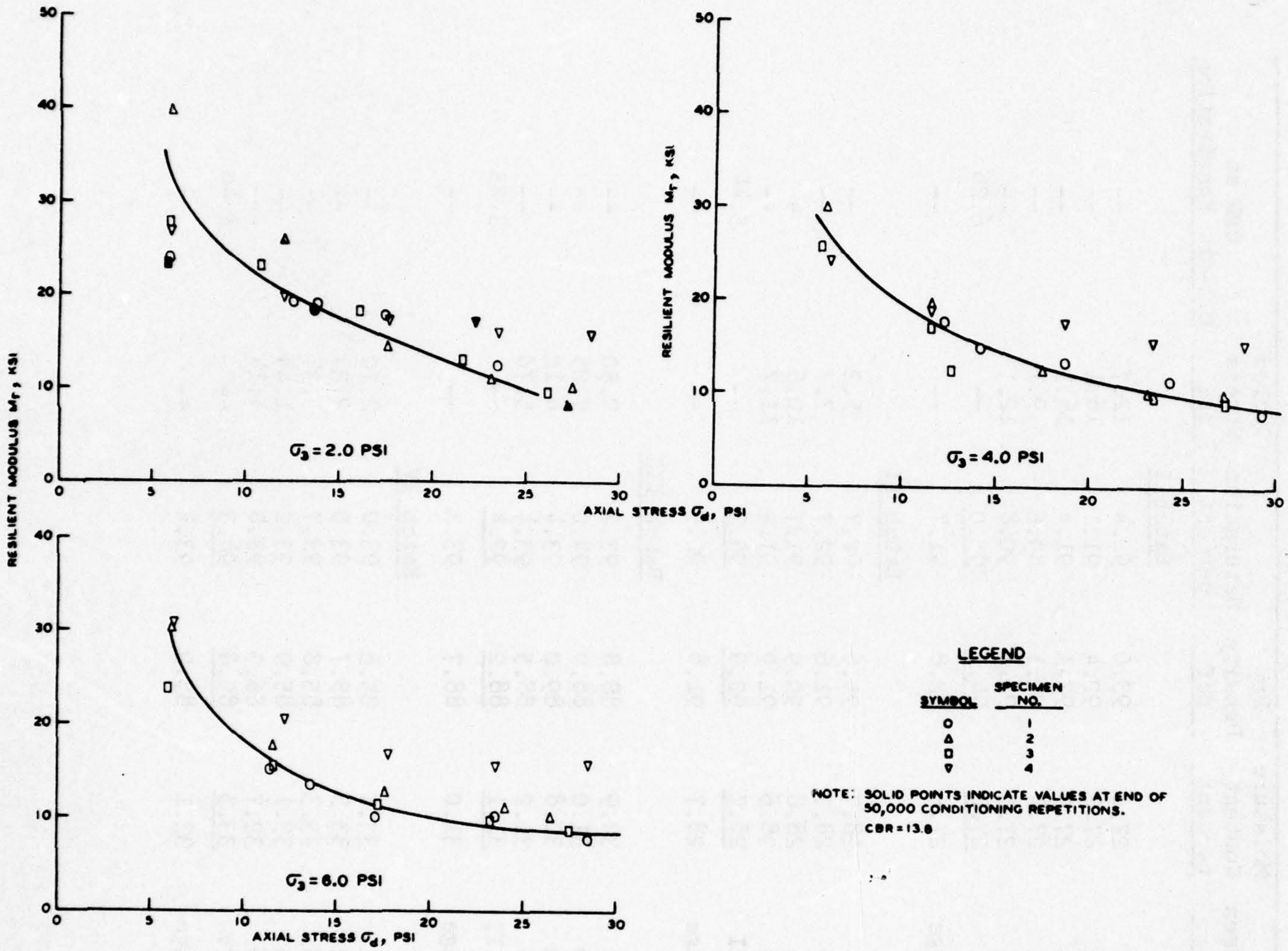

Figure 29. Effect of repetitive stress on resilient modulus for CBR = 13.8 , heavy clay

Table 1

Specimen Identification and Composition Data; Phase I

Specimen No.	Moisture Content percent	Dry Density pcf	Saturation percent	Cycled Stress psi	CBR at 0.1-in. Penetration
			Batch I		
1	27.6	93.0	92.4	12.7	--
2	27.7	92.4	91.1	16.1	--
3	27.9	92.1	91.4	16.1	--
7	27.4	92.1	89.6	9.1	--
17	27.1	93.1	90.8	12.1	--
CBR-I	27.6	94.1	95.0	--	6.26
Average	27.5	92.8	91.7	--	--
			Batch II		
4	28.7	91.6	92.7	5.2	--
5	28.7	91.6	92.7	7.7	--
6	28.8	90.9	91.7	10.6	--
18	28.6	91.9	91.9	11.7	--
CBR-II	28.7	92.9	95.3	--	5.44
Average	28.7	91.8	92.9	--	--
			Batch III		
8	30.9	88.8	93.2	2.50	--
9	31.0	88.9	94.0	5.25	--
10	30.8	89.0	93.4	4.10	--
14	31.2	88.5	93.4	5.70	--
CBR-III	31.1	88.2	92.4	--	3.23
Average	31.0	88.7	93.3	--	--
			Batch IV		
11	33.1	85.8	93.0	2.70	--
12	33.3	85.7	93.0	2.34	--
13	33.3	85.8	93.7	3.37	--
15	33.1	85.9	93.2	1.44	--
16	32.7	86.3	93.0	4.14	--
CBR-IV	33.5	85.8	94.3	--	2.40
Average	33.1	85.9	93.4	--	--

Table 2

Specimen Identification and Composition Data; Phase II

Specimen No.	Moisture Content percent	Dry Density pcf	Saturation* percent	Cycled Stress psi	Percent UCS**	CBR at 0.1-in. Penetration
			Batch V			
1	25.43	96.27	91.90	13.80	35	
2	23.24	97.70	86.95	27.50	70	
3	24.17	95.95	86.70	5.89	15	UCS = 39.3 psi
4	23.19	96.64	86.45	21.91	55.8	
Average of speci-mens	24.13	96.64	88.00			
CBR	23.2	98.2				13.8
			Batch VI			
5	26.78	94.77	93.26	10.00	32.4	
6	26.77	94.89	93.59	21.60	70	
7	26.69	95.52	94.16	4.63	15	UCS = 30.9 psi
8	26.83	94.96	93.92	16.97	55	
Average of speci-mens	26.77	95.04	93.73			
CBR	26.0	95.9				7.5
			Batch VII			
9	31.00	89.15	94.38	3.64	25.3	
10	30.45	89.97	94.52	6.50	45	
11	30.55	89.83	94.53	2.27	15	UCS = 14.4 psi
12	29.69	91.15	94.83	8.73	60	
Average of speci-mens	30.42	90.03	94.57			
CBR	30.4	90.0				3.7

* Based on $G_s = 2.69$ (est).

** Percent unconfined compressive strength represented by cycled stress.

Table 3

Comparison of Modulus Values from Static and Repetitive Tests

Specimen No.	Percent UCS	σ_d for First Cycle psi	Percent Static Strain at Percent UCS	Static Modulus E_s psi	Percent Resilient Strain For First Cycle ε_r	Percent Plastic Strain For First Cycle ε_p	M_r psi	Dynamic Modulus* E_d $(\sigma_d/\varepsilon_r + \varepsilon_p)$	M_r/E_s	E_d/E_s
1	35.0	13.63	0.5	2730	0.07	0.01	19,454	17,037	7.13	6.24
2	70.0	27.39	2.1	1304	0.26	0.16	10,516	6,521	8.06	5.00
3	15.0	5.80	0.2	2901	0.025	0.01	23,208	16,571	8.00	5.71
4	55.0	22.27	1.25	1781	0.10	0.01	22,260	20,245	12.50	11.37
5	32.4	10.02	0.8	1252	0.07	0.115	8,697	5,416	6.95	4.33
6	70.0	21.02	2.5	841	0.46	0.48	4,548	2,236	5.41	2.66
7	15.0	4.22	0.25	1882	0.03	0.01	14,045	10,550	7.46	5.61
8	55.0	14.63	1.3	1125	0.04	0.165	8,857	7,137	7.87	6.34
9	35.0	2.42	0.45	538	0.045	0.02	5,366	3,723	9.98	6.92
10	10.0	1.46	0.27	540	0.03	0.03	4,857	2,433	8.98	4.51
11	15.0	1.95	0.3	650	0.04	0.06	4,854	1,950	7.47	3.00
12	60.0	7.80	1.45	538	0.20	0.16	3,887	2,167	7.22	4.03

* Repeated load tests conducted under a confining pressure of 2.0 psi.

APPENDIX A

This appendix presents tabulations of test data indicating at various stress repetition levels information concerning repeated stress, elastic and plastic strain, and resilient modulus. Table A1 covers data obtained during Phase I testing; Table A2 covers data obtained during Phase II testing.

Table A1

Resilient Triaxial Compression Test*

Phase I, Specimens 1-18

Cycle	Axial Stress psi	Elastic Strain in./in.	Plastic Strain in./in.	Resilient Modulus psi
		Specimen 1		
1	12.4	0.00140	0.00029	8860
5	12.6	0.00158	0.00053	7975
10		0.00160	0.00065	7875
20		0.00164	0.00077	7680
100		0.00176	0.00114	7160
200		0.00185	0.00133	6810
315		0.00188	0.00149	6700
506		0.00193	0.00176	6530
604		0.00195	0.00179	6460
806	12.7	0.00200	0.00197	6350
1000	12.7	0.00208	0.00206	6105
		Specimen 2		
1	16.5	0.00281	0.00075	5870
5	16.6	0.00329	0.00139	5045
10		0.00356	0.00176	4665
20		0.00373	0.00214	4450
28		0.00388	0.00254	4280
50		0.00410	0.00299	4050
90		0.00411	0.00323	4040
154		0.00416	0.00368	3990
575		0.00468	0.00475	3545
800	16.3	0.00479	0.00500	3405
1000	16.1	0.00479	0.00540	3360
		Specimen 3		
1	16.6	0.00340	0.00098	4885
5	16.8	0.00408	0.00185	4120
10	16.8	0.00428	0.00243	3925
100	16.6	0.00478	0.00508	3475
200	16.6	0.00505	0.00603	3285
250	16.6	0.00525	0.00625	3160
301	16.1	0.00518	0.00658	3110
400		0.00538	0.00693	2995
500		0.00533	0.00715	3020
608		0.00530	0.00718	3040
		Specimen 3 (Continued)		
705	16.1	0.00525	0.00725	3065
800		0.00530	0.00735	3040
900		0.00530	0.00743	3040
1000		0.00528	0.00758	3050
		Specimen 4		
1	5.0	0.00057	0.00008	8770
5	5.1	0.00059	0.00014	8645
10	5.2	0.00062	0.00016	8385
20		0.00060	0.00019	8665
102		0.00062	0.00027	8385
201		0.00062	0.00032	8385
400		0.00064	0.00035	8125
503		0.00064	0.00038	8125
600		0.00064	0.00039	8125
800		0.00063	0.00041	8255
1000		0.00064	0.00044	8125
1	7.7	0.00105	0.00007	7335
5	7.8	0.00116	0.00012	6725
10		0.00116	0.00017	6725
71		0.00125	0.00035	6240
		0.00126	0.00038	6190
201		0.00128	0.00049	6095
500		0.00131	0.00064	5955
700		0.00131	0.00070	5955
1000		0.00131	0.00077	5955
		Specimen 5		
1	7.5	0.00102	0.00007	7355
5	7.7	0.00112	0.00018	6875
10		0.00115	0.00026	6695
65		0.00124	0.00042	6210
101		0.00125	0.00047	6160
200		0.00128	0.00056	6015
302		0.00128	0.00063	6015

(Continued)

* Chamber pressure for all specimens = 0.

(Sheet 1 of 4)

Table A1 (Continued)

Cycle	Axial Stress psi	Elastic Strain in./in.	Plastic Strain in./in.	Resilient Modulus psi
		Specimen 5 Continued)		
404	7.7	0.00130	0.00068	5925
501		0.00132	0.00071	5835
603		0.00131	0.00075	5880
700		0.00131	0.00077	5880
800		0.00131	0.00080	5880
920		0.00131	0.00083	5880
1000		0.00131	0.00083	5880
		Specimen 6		
1	10.6	0.00188	0.00038	5640
5		0.00216	0.00068	4905
10		0.00226	0.00085	4690
41		0.00239	0.00125	4435
110		0.00254	0.00154	4175
242		0.00265	0.00183	4000
302		0.00265	0.00193	4000
402		0.00270	0.00205	3925
510		0.00276	0.00215	3840
600		0.00276	0.00224	3840
710		0.00276	0.00233	3840
800		0.00280	0.00239	3785
900		0.00276	0.00245	3840
1000		0.00278	0.00251	3815
		Specimen 7		
1	9.0	0.00068	0.00008	13235
5	9.1	0.00073	0.00013	12465
10		0.00074	0.00014	12300
61		0.00076	0.00021	11975
100		0.00077	0.00023	11820
200		0.00080	0.00028	11375
300		0.00080	0.00031	11375
500		0.00080	0.00035	11375
700		0.00081	0.00038	11235
800		0.00081	0.00041	11235
1000		0.00080	0.00043	11375
		Specimen 8		
1	2.3	0.00045	0.00007	5110
5	2.3	0.00048	0.00018	4790
10	2.4	0.00050	0.00023	4800
62	2.5	0.00051	0.00038	4900
120		0.00051	0.00044	4900
200		0.00052	0.00049	4810
300		0.00052	0.00053	4810
400		0.00053	0.00056	4720
500		0.00051	0.00059	4900
600		0.00052	0.00062	4810
700		0.00053	0.00065	4720
800		0.00052	0.00066	4810
900		0.00052	0.00068	4810
1000		0.00053	0.00069	4720
		Specimen 9		
1	5.2	0.00155	0.00064	3355
5	5.21	0.00169	0.00111	3075
10	5.2	0.00171	0.00132	3040
52		0.00178	0.00186	2920
100		0.00180	0.00207	2890
260		0.00180	0.00243	2890
308		0.00179	0.00249	2905
500	5.25	0.00180	0.00269	2890
603		0.00180	0.00276	2890
700		0.00179	0.00284	2905
800		0.00180	0.00290	2890
900		0.00179	0.00296	2905
1000		0.00180	0.00301	2890
		Specimen 10		
1	4.1	0.00116	0.00038	3534
5		0.00122	0.00068	3360
10		0.00124	0.00083	3305
58		0.00124	0.00120	3305
100		0.00123	0.00131	3335
202		0.00124	0.00149	3305

(Continued)

(Sheet 2 of 4)

Table A1 (Continued)

Cycle	Axial Stress psi	Elastic Strain in./in.	Plastic Strain in./in.	Resilient Modulus psi
Specimen 10 (Continued)				
302	4.1	0.00124	0.00158	3305
402		0.00124	0.00166	3305
503		0.00124	0.00173	3307
605		0.00122	0.00179	3360
700		0.00121	0.00183	3390
804		0.00122	0.00188	3360
1000		0.00122	0.00196	3360
Specimen 11				
1	2.6	0.00107	0.00042	2430
5	2.7	0.00116	0.00080	2330
10		0.00119	0.00098	2270
40		0.00122	0.00135	2215
100		0.00124	0.00161	2175
202		0.00123	0.00182	2195
303		0.00122	0.00195	2215
500		0.00122	0.00212	2215
700		0.00121	0.00225	2230
1000		0.00121	0.00239	2230
Specimen 12				
1	2.13	0.00097	0.00035	2195
5	2.26	0.00102	0.00068	2215
10	2.26	0.00104	0.00083	2175
40	2.31	0.00105	0.00113	2200
101	2.34	0.00105	0.00136	2230
301		0.00103	0.00166	2270
510		0.00102	0.00182	2295
700		0.00101	0.00192	2315
1000		0.00099	0.00204	2365
Specimen 13				
1	3.26	0.00160	0.00073	2040
5	3.37	0.00173	0.00130	1950
10		0.00173	0.00155	1950
44		0.00174	0.00206	1935
100		0.00174	0.00236	1935
200		0.00173	0.00260	1950
Specimen 13 (Continued)				
300	3.37	0.00174	0.00275	1935
500		0.00173	0.00298	1950
700		0.00174	0.00314	1935
840		0.00174	0.00323	1935
1000		0.00174	0.00333	1935
Specimen 14				
1	5.65	0.00258	0.00119	2190
5	5.70	0.00281	0.00205	2030
10		0.00283	0.00241	2015
44		0.00283	0.00335	2015
100		0.00291	0.00380	1960
200		0.00291	0.00435	1960
300		0.00289	0.00463	1970
502		0.00281	0.00508	2030
700		0.00271	0.00531	2105
800		0.00268	0.00540	2125
1000		0.00258	0.00559	2210
Specimen 15				
1	1.21	0.00038	0.00008	3185
5	1.34	0.00042	0.00017	3190
10	1.39	0.00042	0.00021	3310
52	1.45	0.00044	0.00034	3295
100	1.45	0.00044	0.00038	3295
220	1.49	0.00044	0.00047	3385
300	1.45	0.00043	0.00051	3370
500	1.45	0.00044	0.00056	3295
715	1.44	0.00043	0.00060	3350
800	1.44	0.00042	0.00062	3430
1000	1.44	0.00042	0.00065	3430
Specimen 16				
1	4.08	0.00195	0.00090	2090
5	4.11	0.00213	0.00160	1930
10	4.14	0.00218	0.00190	1900
41	4.16	0.00215	0.00255	1935
100	4.16	0.00215	0.00298	1935

(Continued)

(Sheet 3 of 4)

Table A1 (Concluded)

Cycle	Axial Stress psi	Elastic Strain in./in.	Plastic Strain in./in.	Resilient Modulus psi
Specimen 16 (Continued)				
200	4.14	0.00215	0.00335	1925
300		0.00220	0.00355	1880
500		0.00215	0.00385	1925
700		0.00213	0.00405	1945
800		0.00213	0.00413	1945
1000		0.00208	0.00425	1990
Specimen 17				
1	11.91	0.00150	0.00023	7940
5	12.06	0.00166	0.00040	7265
10	12.13	0.00179	0.00048	6775
44		0.00186	0.00071	6520
102		0.00194	0.00085	6255
240		0.00199	0.00104	6095
315		0.00205	0.00113	5915
500		0.00208	0.00129	5830
700		0.00209	0.00139	5805
800		0.00210	0.00144	5775
1000		0.00211	0.00151	5750

Cycle	Axial Stress psi	Elastic Strain in./in.	Plastic Strain in./in.	Resilient Modulus psi
Specimen 18				
1	11.81	0.00261	0.00060	4525
5	11.91	0.00310	0.00116	3840
10	11.99	0.00321	0.00146	3735
66	11.91	0.00360	0.00245	3310
100	11.91	0.00351	0.00276	3395
200	11.91	0.00358	0.00323	3325
303	11.82	0.00360	0.00351	3285
500	11.82	0.00361	0.00388	3275
700	11.74	0.00364	0.00414	3225
1000	11.74	0.00365	0.00441	3215

(Sheet 4 of 4)

Table A2

Resilient Triaxial Compression Test

Phase II, Specimens 1-12

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	Resilient Strain ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 1				
0	0.0000	2.0	0.00	0.00	N.A.	0.682	N.A.
1	0.0001		700.72	214.33	0.306	13.631	19454
10	0.0001		750.81	214.33	0.285	13.631	18156
100	0.0002		800.94	267.92	0.335	13.974	17447
500	0.0003		801.02	267.93	0.334	13.975	17446
1000	0.0004		826.09	267.94	0.324	13.976	16918
5000	0.0005		826.22	267.96	0.324	13.978	16918
10000	0.0006		826.30	267.97	0.324	13.979	16917
20000	0.0007		801.36	267.96	0.334	13.653	17037
30000	0.0009		776.46	267.96	0.345	13.653	17583
40000	0.0011		751.52	250.08	0.333	13.651	18164
50000	0.0011		751.52	250.08	0.333	13.651	18164
100	0.0010		250.50	71.44	0.285	5.849	23349
200	0.0011		651.32	214.32	0.329	12.509	19206
300	0.0011		726.47	232.18	0.320	13.809	19009
400	0.0011		1002.08	339.35	0.339	17.546	17509
500	0.0013		1904.24	643.02	0.338	23.560	12373
600	0.0013	4.0	701.60	232.19	0.331	12.348	17600
700	0.0013		952.19	321.50	0.338	14.298	15015
800	0.0014		1403.30	428.66	0.305	18.684	13315
900	0.0015		2155.39	714.46	0.331	24.373	11308
1000	0.0022		3661.53	1286.59	0.351	29.272	7995
1100	0.0031	6.0	753.05	214.49	0.285	11.390	15125
1200	0.0031		1004.07	321.74	0.320	13.668	13613
1300	0.0032		1681.94	571.98	0.340	17.085	10158
1400	0.0031		2309.47	786.42	0.341	23.591	10215
1500	0.0034		3716.07	1358.50	0.366	28.477	7663

(Continued)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	Resilient Strain ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Pesilient Modulus psi
			Specimen 2				
0	0.0000	2.0	0.00	0.00	N.A.	0.645	N.A.
100	0.0016		2605.34	1138.47	0.437	27.397	10516
500	0.0023		2807.86	1137.78	0.405	27.364	9745
1000	0.0027		3009.63	1279.55	0.425	27.344	9086
3000	0.0034		3011.59	1420.76	0.472	27.307	9067
5000	0.0038		3213.74	1420.05	0.442	27.280	8489
10000	0.0039		3214.22	1419.70	0.442	27.267	8483
20000	0.0043		3215.43	1418.84	0.441	27.234	8470
30000	0.0045		3215.92	1418.64		27.226	8466
40000	0.0046		3216.24	1418.54		27.222	8464
50000			3216.48	1418.49		27.220	8463
100			150.76	70.94	0.471	6.088	40379
200			452.30	195.09	0.431	11.855	26210
300			1206.12	496.59	0.412	17.622	14610
400			2110.76	922.25	0.437	23.229	11005
500			2713.91	1206.02	0.444	27.234	10035
600	0.0047	4.0	201.04	88.69	0.441	6.089	30290
700			603.12	266.07	0.441	11.858	19661
800			1407.32	603.09	0.429	17.627	12525
900			2312.02	993.30	0.430	23.234	10049
1000			2714.18	1206.14	0.444	27.240	10036
1100		6.0	201.05	70.96	0.353	6.090	30292
1200	0.0048		653.43	283.83	0.434	11.539	17659
1300			1407.42	603.14	0.429	17.629	12526
1400			2261.99	957.92	0.423	24.040	10628
1500			2613.92	1135.28	0.434	26.442	10116

(Continued)

(Sheet 2 of 12)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	Resilient Strain ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 3				
0	0.0000	2.0	0.00	0.00	N.A.	0.645	N.A.
1	0.0001		250.15	88.97	0.356	5.805	23208
5	0.0001		250.16	106.77	0.427	5.806	23209
100	0.0000		250.14	106.77		5.806	23210
500	0.0001		250.17	106.77		5.806	23209
1000	0.0002		250.18	106.78		5.807	23210
3000	0.0004		250.23				23208
5000	0.0004		250.24				23208
10000	0.0004		250.24				23207
20000	0.0005		250.26				23204
40000	0.0006		250.29	106.77		5.806	23198
50000	0.0007		250.31	106.77		5.806	23196
100	0.0009		200.30	71.15	0.355	5.802	28966
200	0.0010		500.76	177.89	0.355	11.603	23171
300	0.0011		901.46	355.78	0.395	17.326	19219
400	0.0014		1803.56	676.13	0.375	23.379	12963
500	0.0018		2806.45	1067.96	0.381	27.430	9774
600	0.0020	4.0	225.57	88.98	0.394	5.806	25740
700	0.0020		676.74	231.34	0.342	11.612	17159
800	0.0021		1403.68	498.29	0.355	17.742	12640
900	0.0022		2256.20	836.48	0.371	23.391	10367
1000	0.0025		3009.10	1103.56	0.367	27.430	9116
1100	0.0024	6.0	250.75	88.99	0.355	5.969	23804
1200	0.0025		752.26	249.16	0.331	11.615	15440
1300	0.0025		1504.63	551.72	0.367	17.342	11526
1400	0.0026		2457.80	889.90	0.362	23.393	9518
1500	0.0029		3110.81	1174.75	0.378	27.430	8818

(Continued)

(Sheet 3 of 12)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 4				
0	0.0000	2.0	0.00	0.00	N.A.	0.649	N.A.
1	0.0001		1000.48	392.76	0.393	22.271	22260
10	0.0002		1100.63	464.17	0.422	22.271	20234
100	0.0004		1200.87	464.19	0.387	22.272	18547
500	0.0005		1301.17	499.95	0.384	22.277	17121
3000	0.0008		1301.56	535.68	0.412	22.279	17117
5000	0.0010		1301.72	571.33	0.439	22.274	17111
10000	0.0011		1301.92	571.29		22.271	17106
20000	0.0013		1302.12	571.27		22.269	17102
30000	0.0014		1302.31	571.22		22.266	17097
40000	0.0016		1302.54	571.22		22.266	17094
50000			1302.57	499.82	0.384	22.266	17094
100			225.44	89.26	0.396	6.167	27357
200			601.17	232.07	0.386	12.010	19978
300			1027.03	392.73	0.382	17.853	17383
400			1452.91	571.24	0.393	23.533	16197
500	0.0017		1803.65	714.06	0.396	28.402	15747
600		4.0	250.51	89.27	0.356	6.169	24626
700			601.23	249.96	0.416	11.689	19441
800			1052.18	428.48	0.407	18.668	17742
900			1503.12	607.01	0.404	23.538	15660
1000			1853.89	749.84	0.404	28.408	15324
1100		6.0	200.42	89.28	0.445	6.170	30785
1200			601.26	232.12	0.386	12.340	20523
1300	0.0018		1052.24	392.82	0.373	17.861	16974
1400	0.0018		1528.29	589.22	0.386	23.543	15405
1500	0.0018		1803.92	714.21	0.396	28.414	15751

(Continued)

(Sheet 4 of 12)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ϵ_1, μin./in.	Resilient Strain ϵ_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 5				
0	0.0000	2.0	0.00	0.00	N.A.	0.647	N.A.
1	0.0007		1152.30	356.30	0.309	10.022	8697
5	0.0010		1202.71	356.30	0.296	10.022	8333
20	0.0013		1178.06	356.28	0.302	10.020	8506
100	0.0016		1203.43	356.21	0.296	10.017	8323
500	0.0019		1178.80	356.20	0.302	10.016	8497
1000	0.0021		1153.89		0.309		8680
3000	0.0024		1154.24		0.309		8678
5000	0.0025		1104.22		0.323		9071
10000	0.0027		1104.42		0.323		9069
20000	0.0030		1054.51	356.21	0.338	10.017	9499
30000	0.0032		954.29	320.59	0.336		10496
40000	0.0033		954.39	284.98	0.299		10496
50000	0.0034		904.27	284.98	0.315		11078
100	0.0034		276.31	106.89	0.387	4.364	15795
200	0.0035		376.79	231.60	0.615	9.213	24453
300	0.0035		1356.51	445.36	0.328	13.900	10247
400	0.0042		2966.24	926.12	0.312	18.174	6127
500	0.0067		5040.07	1707.70	0.339	21.756	4317
600	0.0066	4.0	302.39	106.77	0.353	4.516	14934
700	0.0067		982.81	320.32	0.326	9.032	9190
800	0.0068		2343.87	747.38	0.319	13.869	5917
900	0.0071		3882.61	1281.09	0.330	18.139	4672
1000	0.0080		5046.68	1778.47	0.352	20.942	4150
1100	0.0079	6.0	353.26	124.53	0.353	4.513	12776
1200	0.0080		1160.80	373.60	0.322	9.349	8054
1300	0.0081		2498.49	836.12	0.335	13.862	5548
1400	0.0084		4039.08	1351.93	0.335	18.130	4489
1500	0.0090		5051.91	1778.28	0.352	21.340	4224

(Continued)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ϵ_1, µin./in.	Resilient Strain ϵ_3, µin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 6				
0	0.0000	2.0	0.00	0.00	N.A.	0.649	N.A.
1	0.0048		4623.35	3421.48	0.740	21.025	4548
100	0.0190		8411.93	3387.44	0.403	20.609	2450
500	0.0231		7679.51	3166.67	0.412	20.886	2720
1000	0.0251		8208.07	3371.97	0.411	21.206	2584
3000	0.0278		7716.25	3296.28	0.427	21.137	2739
5000	0.0288		7467.11	3224.45	0.432	21.896	2932
10000	0.0299		7217.42	3012.79	0.417	21.095	2923
20000	0.0310		6709.33	2801.71	0.418	20.692	3084
30000	0.0315		6196.43	2521.10	0.407	20.684	3338
40000	0.0318		6198.35	2521.01	0.407	20.683	3337
50000	0.0320		6199.95	2380.12	0.384	20.668	3334
100	0.0318		309.93	105.08	0.339	4.686	15120
200	0.0318		774.85	280.21	0.362	9.060	11692
300	0.0319		2272.96	875.66	0.385	13.278	5842
400			4339.52	1716.23	0.395	17.962	4139
500			5682.85	2171.55	0.382	21.086	3711
600		4.0	361.64	140.11	0.387	4.531	12528
700	0.0320		1291.62	490.40	0.380	8.905	6894
800			1859.94	1120.92	0.603	13.748	7392
900			4339.96	1751.37	0.404	17.965	4139
1000			5580.10	2241.84	0.402	21.091	3780
1100	0.0319	6.0	258.29	87.59	0.339	4.377	16944
1200	0.0319		697.40	262.79	0.377	8.910	12776
1300	0.0319		1937.28	770.85	0.398	14.068	7262
1400	0.0320		3719.78	1471.62	0.396	17.976	4833
1500	0.0320		5166.76	2032.16	0.393	21.336	4129

(Continued)

(Sheet 6 of 12)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	Resilient Strain ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 7				
0	0.0000	2.0	0.00	0.00	N.A.	0.406	N.A.
1	0.0000		300.44	107.11	0.357	4.220	14045
10	0.0001		300.45	107.11	0.357	4.545	15126
100	0.0001		350.53	124.96	0.356	4.707	13428
500	0.0002		325.51	124.96	0.384	4.707	14460
1000	0.0002		325.52	124.96	0.384	4.707	14460
3000	0.0004		350.62	124.97	0.356	4.708	13427
5000	0.0004		300.53	124.97	0.416	4.708	15664
10000	0.0006		375.77	142.84	0.380	4.708	12530
30000	0.0014		250.70	107.09	0.427	4.705	18769
40000	0.0014		275.78	107.09	0.388		17062
50000	0.0014		250.71	89.24	0.356		18766
100	0.0015		275.79	89.24	0.324		17060
200	0.0016		802.43	285.58	0.356	9.248	11526
300	0.0023		1706.27	535.52	0.314	14.281	8370
400	0.0035		3517.41	1106.95	0.315	18.670	5308
500	0.0055		5236.13	1747.82	0.334	21.465	4099
600	0.0053	4.0	327.18	142.74	0.436	4.540	13875
700	0.0054		1132.67	374.68	0.331	9.403	8302
800	0.0056		2618.26	856.32	0.327	13.940	5324
900	0.0060		4231.42	1462.61	0.346	18.634	4404
1000	0.0069		5419.99	1854.23	0.342	21.451	3958
1100	0.0067	6.0	403.29	142.67	0.354	4.698	11648
1200	0.0068		1285.54	445.84	0.347	9.071	7056
1300	0.0070		2722.87	945.11	0.347	13.928	5115
1400	0.0073		4287.19	1497.70	0.349	18.214	4249
1500	0.0075		5145.80	1818.44	0.353	21.043	4089

(Continued)

Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, µin./in.	ε_3, µin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 8				
0	0.0000	2.0	0.00	0.00	N.A.	0.650	N.A.
1	0.0004		1651.28	607.34	0.368	14.626	8857
20	0.0014		3205.77	964.49	0.301	16.653	5195
100	0.0025		3510.09	1070.85	0.305	16.628	4737
500	0.0035		3814.88	1177.48	0.309	16.615	4355
1000	0.0040		3917.33	1248.57	0.319	16.608	4240
3000	0.0049		3920.68	1283.79	0.327	16.596	4233
5000	0.0053		3922.36	1319.26	0.336	16.592	4230
10000	0.0055		3923.34	1319.17	0.336	16.589	4228
20000	0.0063		3926.41	1283.19	0.327	16.986	4326
30000	0.0067		3827.08	1283.01	0.335	16.981	4437
40000	0.0069		3727.30	1247.33	0.335	16.575	4447
50000	0.0072		3526.89	1247.24	0.354	16.573	4699
100	0.0071		327.47	89.10	0.272	4.690	14322
200	0.0072		1032.82	338.57	0.328	9.542	9238
300			2418.38	801.88	0.332	14.231	5885
400			3627.66	1247.37	0.344	18.598	5127
500			4534.69	1568.12	0.346	21.428	4725
600		4.0	377.88	89.10	0.236	4.691	12413
700	0.0073		1284.86	409.88	0.319	9.381	7301
800			2569.79	855.40	0.333	13.910	5413
900			4081.53	1318.70	0.323	18.599	4557
1000			4535.15	1568.18	0.346	21.430	4725
1100		6.0	428.32	124.75	0.291	4.529	10574
1200	0.0074		1461.36	463.36	0.317	9.382	6420
1300	0.0074		2721.23	908.90	0.334	13.911	5112
1400	0.0075		3930.96	1354.43	0.345	18.197	4629
1500	0.0076		4737.78	1532.70	0.324	21.434	4524

(Continued)

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Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 9				
0	0.0000	2.0	0.00	0.00	N.A.	0.647	N.A.
1	0.0002		452.10	142.56	0.315	2.426	5366
5	0.0004		552.71	142.57	0.258	2.911	5267
10	0.0005		552.74	142.57	0.258	2.911	5267
20	0.0005		552.76	142.57	0.258	2.911	5267
100	0.0010		804.38	178.22	0.222	3.640	4525
500	0.0015		804.81	178.23	0.221	3.640	4523
1000	0.0017		779.80	178.24	0.229	3.641	4669
3000	0.0020		754.87	178.25	0.236		4823
5000	0.0021		757.00	178.26	0.236		4823
10000	0.0024		704.86	178.26	0.253		5166
20000	0.0027		654.73	178.26	0.272		5562
30000	0.0029		680.05	178.27	0.262	3.642	5355
40000	0.0031		654.98	178.27	0.272	3.642	5560
50000	0.0033		604.72	160.43	0.265	3.641	6022
100	0.0033		327.55	89.13	0.272	2.104	6423
200	0.0033		781.11	196.09	0.251	4.208	5387
300	0.0036		1537.49	374.36	0.243	6.312	4105
400	0.0055		3030.23	820.43	0.271	8.586	2834
500	0.0078		4556.04	1356.66	0.298	10.224	2244
600	0.0082	4.0	430.43	124.92	0.290	2.271	5276
700	0.0083		1316.82	374.80	0.285	4.705	3573
800	0.0086		2583.78	785.38	0.304	7.140	2763
900	0.0094		4157.48	2498.21	3.006	9.741	2343
1000	0.0115		5690.77	1855.62	0.326	11.187	1966
1100	0.0117	6.0	330.33	107.08	0.324	2.109	6384
1200	0.0118		1118.11	356.94	0.319	4.380	3917
1300	0.0120		2490.91	785.21	0.315	6.812	2735
1400	0.0122		3711.90	1231.18	0.332	8.756	2359
1500	0.0127		4782.01	1569.86	0.328	10.535	2203

(Continued)

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Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ϵ_1, μin./in.	Resilient Strain ϵ_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 10				
0	0.0000	2.0	0.00	0.00	N.A.	0.454	N.A.
1	0.0003		300.68	107.09	0.356	1.460	4857
5	0.0012		1003.21	214.19	0.214	3.732	3720
10	0.0027		2511.74	642.79	0.256	5.845	2327
20	0.0035		2815.41	642.83	0.228	6.528	2319
100	0.0050		3826.79	714.34	0.187	6.497	1698
500	0.0062		2671.77	785.57	0.294	6.494	2431
1000	0.0068		2572.51	749.79	0.291	6.492	2524
3000	0.0075		2322.12	678.30	0.292	6.491	2795
5000	0.0081		2020.41	642.56	0.318	6.490	3212
10000	0.0085		1819.10	571.16	0.314	6.490	3568
20000	0.0091		1567.36	571.20	0.364	6.491	4141
30000	0.0094		1466.68	464.10	0.316	6.491	4426
40000	0.0096		1315.22	392.73	0.299	6.492	4936
50000	0.0098		1264.86	392.73	0.310	6.492	5133
100	0.0098		202.39	71.45	0.353	2.275	11240
200	0.0099		531.31	178.62	0.336	4.387	8258
300	0.0099		986.74	321.52	0.326	6.662	6752
400	0.0100		1619.39	528.70	0.326	8.937	5519
500	0.0101		2307.98	732.30	0.317	10.398	4505
600	0.0102	4.0	278.40	71.45	0.257	2.275	8173
700	0.0103		683.39	232.22	0.340	4.388	6421
800	0.0104		1240.35	428.69	0.346	6.662	5371
900	0.0105		177.21	625.18	3.528	8.937	50433
1000	0.0107		2501.84	839.47	0.336	10.561	4221
1100	0.0109	6.0	253.27	89.30	0.353	2.275	8981
1200	0.0110		658.54	214.33	0.325	4.387	6661
1300	0.0111		1215.87	428.68	0.353	6.662	5479
1400	0.0112		1849.46	643.04	0.348	8.775	4745
1500	0.0115		1216.45	857.45	0.705	10.239	8417

(Continued)

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Table A2 (Continued)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	Resilient Strain ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 11				
0	0.0000	2.0	0.00	0.00	N.A.	0.649	N.A.
1	0.0006		401.05	107.09	0.267	1.947	4854
5	0.0009		451.32	107.09	0.237	2.272	5033
10	0.0009		451.34	107.09		2.272	5033
23	0.0011		451.41	107.10		2.110	4673
100	0.0013		451.51			2.272	5032
500	0.0016		401.48		0.267	2.272	5659
1000	0.0018		401.56		0.267	2.272	5657
3000	0.0022		351.49	89.24	0.254	2.271	6462
5000	0.0025		351.62	89.23	0.254	2.271	6459
10000	0.0027		326.55	89.23	0.273	2.271	6955
20000	0.0031		276.42	71.38	0.258	2.270	8213
40000	0.0036		251.42	71.37	0.284	2.270	9028
50000	0.0037		251.45	71.37	0.284	2.270	9027
100	0.0038		251.46	71.36	0.284	2.269	9024
200	0.0041		779.78	196.24	0.252	4.539	5820
300	0.0053		1954.36	446.08	0.228	6.648	3402
400	0.0077		3635.35	928.51	0.255	8.769	2412
500	0.0106		5367.77	1588.66	0.296	10.548	1965
600	0.0109	4.0	329.26	107.15	0.325	2.111	6413
700	0.0110		1013.27	285.71	0.282	4.385	4327
800	0.0113		2179.15	642.81	0.295	6.658	3055
900	0.0119		3600.13	1124.68	0.312	8.927	2480
1000	0.0127		4668.98	1498.98	0.321	10.380	2223
1100	0.0128	6.0	279.13	89.27	0.320	2.110	7561
1200	0.0129		685.24	303.50	0.443	4.383	6396
1300	0.0131		2106.92	678.35	0.322	6.654	3158
1400	0.0135		3352.04	1124.48	0.335	8.924	2662
1500	0.0140		4370.03	1441.93	0.330	10.380	2375
900	0.0109	4.0	1874.32	624.84	0.333	8.928	4763
1500	0.0120	6.0	2434.14	856.99	0.352	10.228	4202

(Continued)

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Table A2 (Concluded)

Cycle	Permanent Strain in./in.	Chamber Pressure psi	Resilient Strain ε_1, μin./in.	Resilient Strain ε_3, μin./in.	Poisson's Ratio	Axial Stress psi	Resilient Modulus psi
			Specimen 12				
0	0.0000	2.0	0.00	0.00	N.A.	0.487	N.A.
1	0.0016		2005.41	571.45	0.285	7.796	3887
5	0.0022		2407.95	714.36	0.297	8.772	3643
10	0.0026		2609.66	714.46	0.274	8.774	3362
23	0.0034		2611.62	714.11	0.273	8.765	3356
100	0.0044		2714.80	856.68	0.316	8.760	3227
500	0.0054		2616.88	785.07	0.300	8.755	3346
1000	0.0059		2618.26	856.32	0.327	8.753	3343
3000	0.0066		2519.40	856.19	0.340	8.750	3473
5000	0.0070		2419.48	784.79	0.324	8.749	3616
10000	0.0074		2218.86	713.39	0.322	8.748	3943
20000	0.0080		2018.37	713.39	0.353	8.748	4334
30000	0.0084		1918.17	642.03	0.335	8.747	4560
40000	0.0086		1817.63	570.72	0.314	8.748	4813
50000	0.0089		1717.08	642.03	0.374	8.747	5094
100	0.0087		201.98	71.36	0.353	2.269	11234
200	0.0087		504.96	178.39	0.353	4.376	8666
300	0.0088		1009.97	338.93	0.336	6.483	6419
400	0.0088		1590.75	570.82	0.359	8.751	5501
500	0.0088		2020.05	713.52	0.353	10.372	5134
600	0.0089	4.0	227.27	71.36	0.314	2.269	9985
700	0.0090		580.84	214.07	0.369	4.376	7534
800	0.0090		1085.97	374.63	0.345	6.645	6119
900	0.0090		1616.37	570.86	0.353	8.914	5515
1000	0.0091		1919.48	695.73	0.362	10.697	5573
1100	0.0092	6.0	252.60	71.37	0.283	2.270	8986
1200	0.0093		606.27	214.11	0.353	4.378	7221
1300	0.0093		1111.56	392.52	0.353	6.647	5980
1400	0.0094		1591.71	553.10	0.347	8.917	5602
1500	0.0095		2021.43	713.67	0.353	10.376	5133

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